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TACTILE DISPLAY FOR AIRCRAFT CONTROL

Don H. Ross, et al

Sanders Associates, Incorporated

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TACTILE DISPLAY FOR AIRCRAFT CONTROL

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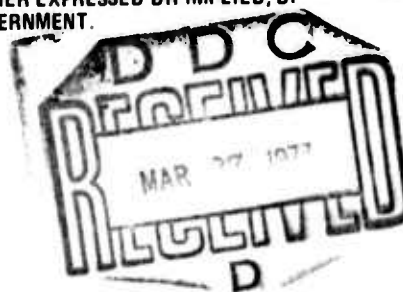
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Prepared By

D. Ross - R. Sanneman



SANDERS
ASSOCIATES, INC.

95 Canal Street - Nashua, New Hampshire 03060

And

Dr. W. Levison - R. Tanner - Dr. T. Triggs

BEHAVIORAL SCIENCE DIVISION - BOLT-BERANEK AND NEWMAN, INC.
Moulton Street - Cambridge, Massachusetts

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13. ABSTRACT In current aircraft, nearly all the flight parameter information available to the pilot is transmitted to him visually, whether under visual contact or instrument flying conditions. It has long been recognized that during instrument flying conditions the task of scanning just the essential instruments is a taxing, fatiguing one. It may be that displays using information from other modalities can alleviate the demands of this task. Tactual presentations possess considerable promise of being suitable substitutes for visual displays in flight-control applications. The goal of this program is to develop tactual displays that can be utilized for flight control. This work is being conducted in three distinct phases. (a) Review and selection of elemental tactile transducers (tactors) for operation in arrays. (b) Development of tactile display configurations suitable for application to the aircraft problem. (c) Evaluation of the man/machine tracking performance for multiaxis data utilizing the tactual arrays together with suitable dynamic simulation of aircraft motions. Phases a and b are essentially complete and are reported herein, and Phase c is just getting underway.			

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TABLE OF CONTENTS

<u>Paragraph</u>		<u>Page</u>
ACKNOWLEDGMENTS		
SUMMARY		
SECTION 1		
	INTRODUCTION	1
1.1	Problem Definition	2
1.1.1	Display Requirements in Modern Aircraft	2
1.2	Some Properties of Visual Displays	4
1.3	Non-Visual Information Displays	5
1.3.1	Auditory Flight Displays	5
1.3.2	Tactual Flight Displays	6
1.3.3	Tactual Tracking Studies	7
1.3.3.1	Tactual Versus Visual Tracking	7
1.3.3.2	Tactical Display Location	8
1.3.3.3	Type of Stimulation	9
1.3.3.4	Frequency of Stimulation	9
1.3.3.5	Stimulus Coding	10
1.3.3.6	Display-Control Compatibility	11
1.3.3.7	Masking and Adaptation	11
1.3.3.8	Other Relevant Variables	11
SECTION 2		
	INITIAL SELECTION OF DISPLAY PARAMETERS	13
2.1	Tactors	13
2.1.1	Electrotactors	14
2.1.2	Vibrotactors	19
2.1.3	Tactor Experiments	21
2.1.3.1	Single Electrotactor	21
2.1.3.2	Multiple Tactors	26
2.1.3.3	Polarization Effects	28
2.1.4	Biphasic Constant Current Drive	31

TABLE OF CONTENTS (Cont)

<u>Paragraph</u>		<u>Page</u>
2.2	Display Configuration Development	32
2.2.1	Display Formats	32
2.2.2	Initial X-Y Display Observations	33
2.2.3	Bank Angle Display	36
SECTION 3 HARDWARE DESCRIPTION		41
3.1	Simplified Block Diagram	41
3.2	Functional Block Diagram	52
3.2.1	Manual Control	52
3.2.2	Automatic Control	52
3.2.3	Clock	57
3.2.4	Multiplexer	57
3.2.5	Format Control	58
3.2.6	Tactile Pulse Generator	59
3.2.7	Electrotactor Drivers	60
3.2.8	Bimorph Control Logic	60
SECTION 4 PRELIMINARY DISPLAY EVALUATION		63
4.1	Circle Display	63
4.2	Polarized X-Y Display, Number and Rate Judgments	69
4.2.1	Judgments of Number of Tactors	69
4.2.2	Rate Judgments	74
4.3	Tracking Experiments	74
4.3.1	Polarized X-Y Display, 0.75 Inch Spaced Electrotactors	77
4.3.2	Polarized X-Y Display 1.25 Inch Spaced Electrotactors	77
4.3.3	Polarized X-Y Display, 1.125 Inch Spaced Bimorphs	79
4.3.4	Non-Polarized X-Y Display, 2.5 Inch Spaced Electrotactors	79
4.3.5	Visual Tracking Experiment	79
4.3.6	Non-Polarized H Display, Electrotactors	80
4.4	Conclusions	80
SECTION 5 PROGRAM PLAN FOR REMAINDER OF CONTRACT		81

TABLE OF CONTENTS (Cont)

<u>Paragraph</u>		<u>Page</u>
	SECTION 6	
	EXPERIMENTAL PROGRAM	83
6.1	Simulation Facility	83
6.1.1	Experimental Configuration	83
6.1.2	Displays and Controls	85
6.2	Experimental Tasks	85
6.2.1	Tracking Tasks	85
6.2.2	Visual Search Task	88
6.3	Tentative Experimental Plan	88
6.3.1	Final Preliminary Experiment	88
6.3.2	Initial Training	89
6.3.3	Experiment 1: Final Selection of Display Parameters	89
6.3.4	Experiment 2: Tracking with Visual Search Task	90
6.3.5	Additional Experimentation	90
	SECTION 7	
	ANALYSIS PROCEDURES	91
7.1	Primary Data Analysis	91
7.1.1	Variance Scores	91
7.1.2	Amplitude Distribution Densities	91
7.1.3	Power Spectra	92
7.1.4	Observation Noise Spectra	93
7.2	Model Analysis	93
7.2.1	Principal Features of the Model	93
7.2.2	Model-Matching Techniques	96
	REFERENCES	99
	DISTRIBUTION LIST	105

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
2-1	Tactor Stimulus and Display Periods	16
2-2	Electrotactor Test Models	18
2-3	Electromechanical Solenoid Vibrotactors	20
2-4	Bimorph Vibrotactor Array	22
2-5	Exploded View of the Bimorph Vibrotactor	23
2-6	Single Tactor Evaluation Circuit	24
2-7	Skin Stimulation Electrical Signals	29
2-8	Three-Axis Polarized Display Format	34
2-9	Three-Axis Nonpolarized Display Format	34
2-10	Multiaxis Tactile Displays	35
2-11	Multidisplay Control Unit Block Diagram	37
2-12	Electrotactor Circle Bank Angle Display	38
2-13	Multidisplay Control Unit	39
3-1	Two-Axis Tactile Control System	42
3-2	Polarized X-Y Electrotactile Display	43
3-3	Polarized X-Y Vibrotactile Display	44
3-4	Nonpolarized X-Y Vibrotactile Display	45
3-5	Nonpolarized X-Y Electrotactile Display	46
3-6	Nonpolarized H Vibrotactile Display	47
3-7	Nonpolarized H Electrotactile Display	48
3-8	Tactile Display Simplified Block Diagram	49
3-9	Tactile Display Functional Block Diagram	53
3-10	Control Logic Unit - Front View	55
3-11	Ripple Rate vs \dot{T} Signal	56
3-12	Control Logic Unit - Rear View	61
3-13	Tactile Display Unit	62
4-1	Circle Display - Comparison of Performance at Different Spacings	65
4-2	Circle Display - Comparison of Gross Error Frequency at Different Spacings	66
4-3	Circle Display - Comparison of Average Error at Different Spacings	67
4-4	Circle Display - Reversal Errors as a Function of ITI and Spacing	68
4-5	Step Input Tracking Experiments	78
5-1	Program Schedule	82
6-1	Experimental Configuration	84
6-2	Idealized Display Format	86

LIST OF TAPLES

<u>Table</u>		<u>Page</u>
2-1	Tactor Parameter Comparisons	15
2-2	Electrotactor Test Model Parameters	17
4-1	Relation of Tactor Rate and Intertactor Interval	70
4-2	Single Axis Judgments of Number of Tactors	72
4-3	Two Axis Judgments of Number of Tactors	73
4-4	Single Axis - Rate Judgments	75
4-5	Two Axis - Rate Judgments	76

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SUMMARY

In current aircraft, nearly all the flight parameter information available to the pilot is transmitted to him visually, whether under visual contact or instrument flying conditions. It has long been recognized that during instrument flying conditions the task of scanning just the essential instruments is a taxing, fatiguing one. It may be that displays using information from other modalities can alleviate the demands of this task. Furthermore, the importance of maintaining continuous attention to the visual scene outside the cockpit is being increasingly realized for a number of situations. Traditional panel-mounted visual displays do not permit this, whereas display of information to other modalities could free the eyes substantially from tasks inside the cockpit.

Tactual presentations possess considerable promise of being suitable substitutes for visual displays in flight-control applications. The goal of this program is to develop tactual displays that can be utilized for flight control.

This work is being conducted in three distinct phases.

- a. Review and selection of elemental tactile transducers (tactors) for operation in arrays.
- b. Development of tactile display configurations suitable for application to the aircraft problem.
- c. Evaluation of the man/machine tracking performance for multiaxis data utilizing the tactual arrays together with suitable dynamic simulation of aircraft motions.

At this time Phases a and b are essentially complete and Phase c is just getting underway.

Much dependence has been placed on the results of a literature survey in order to limit the number of tactor types requiring experimental evaluation. Tactor arrays utilizing either piezo-electric/bimorph elements or coaxial-electrode electrocutaneous transducers have been chosen and multiaxis display configurations

(Section 2.2) have been generated with the goal of optimizing performance, while at the same time minimizing system complexity, size, weight, and cost. Excitation formats that are analogous to known perceptions have been sought to minimize subject training time. Evaluation of the candidate displays as described in Section 6 will utilize instrument rated pilots.

Based on the results of this evaluation, a preliminary design specification and program plan will be developed describing a tactile system that would be evaluated in a sophisticated aircraft flight simulator in a follow-on phase.

Since formal evaluation of the tactual flight control displays is just getting underway, work to be reported on in this document will include a description of the developed equipment and preliminary tests and observations as well as detailed procedures for conducting and evaluating the "formal" psychophysical experiments.

SECTION I

INTRODUCTION

During the last two decades, significant research and developmental efforts have been devoted to improving display techniques used in supplying information to the human operator in the flight environment. Almost invariably, this effort has been devoted to the visual domain to the relative neglect of the other sense modalities.

We suggest that not only is data presentation to other sense modalities possible, but for some aircraft flight situations, displays using other modalities could lead to important gains in performance. Therefore, we have undertaken to explore the feasibility of tactical flight displays.

It is reasonable to assume that simple or single dimensional control tasks can be adequately controlled using other than visual displays, but this cannot be assumed for more complex displays. Accordingly, evaluation of multi-dimensional tactual displays which represent several different ways of presenting information for control of the aircraft flight path is now underway.

A systematic evaluation of the feasibility of tactual displays probably should be carried out in three separate phases: (1) initial design and laboratory evaluation, (2) evaluation utilizing full-task simulation and, finally, (3) flight test.

The work now in progress under our current contract covers the first phase of such a program, and is described herein. We have developed a flexible display apparatus which has allowed us to design and evaluate several different tactual display configurations. A comparative experimental evaluation is planned that will permit the selection of the superior display configuration(s). Analysis of the tracking data using an optimal control model will allow us to evaluate the pilot's control strategy, and various pilot-related parameters. This will permit us to formulate some generalizations about performance using tactual displays. Also we plan to compare the tactual display selected with the standard visual displays used in the same basic flight control task. The series of experiments, now underway will allow initial evaluation of the feasibility of tactual displays and will provide an indication of the desirability of pursuing the later phases of evaluation.

This report covers the accomplishments of our first six months of effort, and our detailed plans for the remainder of the program.

Work under the initial six month period was accomplished physically at Sanders Associates and was culminated by the completion of four two-axis displays, together with the A-D input buffer, tactor control-logic and driver electronics. Electrocutaneous and bimorph tactors are utilized in each of two configurations. The first configuration uses thirteen (13) tactor elements in an X-Y array with the tactors in fixed positions. The second "movable-tactor-display" has provisions for driving as many as thirteen (13) transducers, and allows evaluation of tactor separation for X-Y and H display configurations.

At this time, the equipment is being integrated with the tracking facility at Bolt, Beranek and Newman.

1.1 PROBLEM DEFINITION

1.1.1 DISPLAY REQUIREMENTS IN MODERN AIRCRAFT

In current aircraft, nearly all the flight parameter information available to the pilot is transmitted to him visually, whether under visual contact or instrument flying conditions. It has long been recognized that during instrument flying conditions the task of scanning just the essential instruments on a standard panel is a taxing, fatiguing one (Chapanis et al., 1949, p. 251). Since the late 1950's there have been several trends away from reliance on the standard panel-mounted displays. The Air Force first expended significant effort on designing an integrated instrument panel utilizing vertical displays in order to reduce the time required to scan the instrument array and to reduce the incidence of pilot-reading errors, particularly with regard to altitude.

Although most integrated displays contributed to a reduction of the "within-panel" scanning load, other related flight display problems were being experienced. As aircraft increased in weight, velocity and vertical speeds, there was a growing realization that, on approach to landing, the pilot should be able to maintain his gaze continuously out of the cockpit at the flight path ahead. The requirement to alternate attention between the instrument panel and the external world handicaps this maintenance of attention outside the cockpit, which is so important particularly under marginal visibility conditions. As systems become more automatic, the pilot will be used more and more as a visual monitor, and this visual requirement will continue to be important.

In response to this need, "head-up" displays began to be developed. These displays project needed flight parameter information on the pilot's windshield so that he can maintain attention to the flight path ahead while having flight display information immediately available. The projected displays can be collimated to allow the pilot to maintain visual focus at infinity. This type of display, although

eliminating the shifting of gaze and eye refocussing (accommodation), has not met with extensive use except in the very limited application of military aerial gun sights, although development work continues.

Investigation has shown that the minimum time required to accommodate from outside the cockpit to the instrument panel, read an instrument, and then return to viewing the external scene is approximately 2.5 seconds (Gabriel and Burrows, 1968). Such large time measures indicate that this transitioning constitutes a significant loss in the time available to the pilot for actually processing visual information.

Mid-air collisions frequently can be attributed to the fact that pilots were not maintaining sufficient viewing of the outside scene. Zeller and Burke (1968) found that 80% of military mid-air collisions occur in daylight under contact conditions. Thus, neither poor visibility nor increasing air speeds can be major contributing causes of mid-air collisions, (Tibbs, 1962); it seems fair to say that lack of external viewing is a major factor. Pilots tend to use extra-cockpit visual information only a small proportion of the time available (Lybrand et al., 1958).

That maintenance of attention to the external scene around the cockpit is still a critical problem is attested by the fact that the Federal Aviation Agency is currently considering an amendment on this topic to Federal Aviation Regulations. Such an amendment would provide for mandatory time-sharing scan training to increase the effective time the pilot looks out the window. Time-sharing here refers to alternating attention between inside-the-cockpit information and external-scene information. Studies (Pfeiffer et al., 1963; Gabriel and Burrows, 1968) have shown that appropriate training can improve skill in time-sharing, scanning the outside scene, and hazard detection. However, such gains are limited to the extent to which they can be exploited. The requirement for transitioning provides a limit to the effectiveness of time-sharing.

In the military situation, two types of operational conditions are even more critically dependent on maintenance of visual attention outside of the cockpit. Close-in ground battlefield support by aircraft of many different types constitutes a particularly important circumstance for continued maintenance of attention out of the cockpit. For an anecdotal operational description, see Shore (1969, pp. 86 - 90).

Of even greater importance is the emphasis that both the Air Force and Navy have recently given to the need for development of air superiority aircraft, as represented by the F-15 and F-14. Such aircraft will probably be capable of carrying missiles, for use in the aerial-combat (dogfight) situation, that would permit target acquisition and weapons lock-on at angles well off the longitudinal axis of the aircraft. In the dogfight, there has always been a high premium on the pilot maintaining constant direct visual contact with the adversary. This has been shown to be no less important in modern generation aircraft, and persists even though air-to-air missiles are being developed that are slewable and as such do not require

direct orienting of the aircraft towards the target before release of the weapon. This requirement for direct visual contact means that little or no opportunity is available to the pilot to obtain display information from the usual panel-mounted display or head-up displays. The latter displays are feasible only for limited forward-looking fields of view (about 15° visual angle).

One proposal that has received attention recently is the use of helmet-mounted visual displays utilizing small-sized cathode ray tubes; on these, information can be displayed to the pilot continuously no matter what the orientation of his head relative to the axes of the aircraft. These displays have achieved relatively high brightness levels and low weight and can be considered a feasible solution. However, they have the inherent disadvantages of adding additional weight to the helmet, which is undesirable particularly in high-g maneuvers, of being a hazard during ejection, and of introducing the possibility of interfering with the pilot's vision through binocular rivalry effects.

Displays to sense modalities other than vision have the advantage of presenting continuous information to the pilot independent of his head position and eye orientation but probably would not suffer any of the disadvantages described for helmet-mounted displays. Not only can display of information to other modalities free the eyes substantially from tasks inside the cockpit, it is reasonable to expect that such displays could alleviate the demands of the visual scanning task as well. The non-visual display provides a close coupling between the stimulus and the operator.

1.2 SOME PROPERTIES OF VISUAL DISPLAYS

It is a fair statement to say that the visual sense is truly dominant in the area of information displays. It has a number of properties that account for this. Principal among these is the spatial characteristic of this modality, i.e., its ability to place objects accurately in space and to allow magnitudes to be represented on a linear geometric scale. It also has very fine resolution capabilities.

However, this emphasis on visual displays has led to the evolution of systems that require very complex arrays of visual displays. The aircraft cockpit and plant process control rooms provide the best two examples of such complexity. The human operator gains information serially from the separate displays by scanning across the array and gathering data from each instrument in turn. This scanning requirement allows the operator to select the specific information required from the maze of information available, but at the cost of a considerable workload. It has long been recognized that instrument flight is demanding and that, at crucial stages of the flight (e.g., during letdown procedures), it taxes the limit of the operator's information processing capacity. A good deal of this workload can be attributed to the scanning requirements. Senders (1955, 1964) has analyzed the task load of visual instrument scanning in information theoretic terms.

This is not to say that the ability to make eye movements per se is the limiter of performance in such situations, although eye-movements do take a finite time. It is more appropriate to regard the human in such situations as being limited by his central information processing capacity. However, when arrays of visual displays are used, some of the pilot's capacity is taken up by the need to organize the visual scan around the array and to apply the appropriate scaling and meaning to each indicator in turn.

1.3 NON-VISUAL INFORMATION DISPLAYS

Two other modalities, the tactual and auditory senses, seem to hold good promise for use in information displays. The olfactory, taste and vestibular systems must be regarded as relatively unimportant for such applications.

Both the tactual and auditory senses are capable of permitting relatively fine discriminations on the dimensions of frequency, intensity and duration. For a discussion of the parallels between the auditory and tactual senses, see Békésy, 1959. Information can also be coded in these systems according to the pattern and spectral composition of the stimulation. Location is a suitable coding dimension in the tactual modality since stimulators can be positioned over large areas of the body; unfortunately, absolute spatial position is more difficult to represent auditorily. However, by suitable intensity and phase differences between sounds occurring at the two ears, the location of the composite sound occurring within the head can be varied. Such dichotic stimulation can only yield a relatively small number of distinct spatial locations.

Either auditory or tactual (vibrotactile or electrotactile) displays have been proposed for a number of different applications. These include warning signals, sensory aids for the blind either as navigating devices or as substitutes for Braille, computer output displays, sonar, vehicle control, speech displays for the deaf, a Morse code substitute, and communication in noisy environments. In the field of aircraft displays, both auditory and tactual displays have been studied for system applications. However, only the auditory sense has been subjected to any real systematic study.

1.3.1 AUDITORY FLIGHT DISPLAYS

Tonal signaling systems as flight displays, have been studied in several different contexts, although only one simple application has found widespread use. The radio range signaling system makes use of frequency discrimination to display a single-variable tracking signal, namely, flight direction. Developmental work has been carried out on more complex displays in order to supply to the pilot all required information to enable him to maintain a required flight path. This was referred to as flying by auditory reference (FLYBAR) (Forbes et al., 1945; Flynn et al., 1945). This program, although it achieved significant progress towards a feasible system, did not yield an operational system beyond the experimental stage.

At least one of the systems developed for displaying the necessary flight parameters yielded performance in a Link Trainer that was comparable with the usual visual instrument panel but only flight along a straight course was studied. Although definite evidence is not present in the literature, it is reasonable to speculate that there were two contributing reasons to the lack of final success of the project. First, when the pilot was required to perform the three different types of action required by the display in a very demanding task, the standard visual display yielded superior performance than the best auditory display. Second, aural communications are of such importance both within the cockpit and with ground stations that, unless an auditory display should show significantly superior performance, it could not be justified because of possible interaction with speech communications.

1.3.2 TACTUAL FLIGHT DISPLAYS

Tactual displays can offer two possible advantages over auditory displays for presentation of basic flight control data. First, tactual displays should not interfere in any real way with speech communications. Second, the tactual presentation is not limited in its ability to present information in a spatial pattern. This could be important in striving for realism in a display that is presenting information on vehicle orientation, attitude and location in space.

Ballard and Hessinger (1954) proposed a vibratory display system for aircraft control. They used four vibrators mounted on the thumb, each driven at one of three frequencies. Two of the vibrators provided roll information and two provided pitch. The frequency of vibration indicated the magnitude of the error, and the direction of error was indicated by the particular vibrator activated. Ballard and Hessinger installed their device in a Link Trainer, but apparently no results of the evaluation have been reported in the open literature.

Other applications of tactual displays to vehicle control have supplied vibratory information as supplementary information to the primary visual display. One such aircraft control experiment by Hirsch and Kadushin (1968) presented rate-of-error information tactually and error information visually. The controlled dynamics were representative of aircraft characteristics. When the tactual display was added to only one dimension, a small but significant improvement resulted. When added to a second tracking dimension, subjects became confused by the display, probably because of the lack of spatial separation between the vibrators for the two dimensions. The tactual display consisted of two on-off vibrators on the thumb and index fingernails of the hand holding the control stick. Fenton (1966) used a tactile display to give headway information in car following. The display consisted of kinesthetic force from a moving button mounted in the handle of a control stick. The addition of the display greatly reduced the headway variation, particularly when quickening was added.

1.3.3 TACTUAL TRACKING STUDIES

In addition to those relating specifically to vehicle control, a number of experiments dealing with the characteristics of tactual tracking have been reported. The majority of these, like all the studies on vehicle control, had the difficulty that they relied on the overall measurement of system error for performance measurement. As Hill (1970) points out, while such overall measurements are adequate for comparing performance within a given experiment where command-signal bandwidth and amplitude as well as the plant dynamics are constants, it is not satisfactory for comparing displays evaluated in experiments where these parameters are all different. Hill (1970), Weissenberger and Sheridan (1962), and Bliss (1967) all utilized describing function analysis to characterize the operator's performance of the system. This enabled the gain and time delay of the human using a given display to be evaluated more or less independently of the controlled dynamics and properties of the input signal. Such analysis is very desirable if comparison is to be made from one experiment to another and from display to display. Application of even more sophisticated techniques of analysis, where the operator's performance can be also described in terms of the observational noise in the operator's input system (Levison, 1971), allows the perceptual effects of any one display to be directly reflected in a single parameter of a model. This affords an even more detailed description of the human's performance independent of the specific situation except for the particular display characteristics. What information can be gained from tracking studies will be described later.

1.3.3.1 Tactual Versus Visual Tracking

In a number of the above studies, evaluation of tactual tracking performance has been made using visual tracking performance as a reference (Howell and Briggs, 1959; Bliss et al, 1966a; Seeley and Bliss, 1966; Bliss, 1967; Hill, 1970). In some, attempts were made to use visual displays that were equivalent to the tactual displays used (in spatial layout, dimension of coding used, etc.). Howell and Briggs found that vibrotactile and a similarly quantized visual display gave similar performance for one-dimensional tracking. In a two-dimensional task, Seeley and Bliss found that quantized spatially-coded tactile and visual displays gave very similar results over a range of input signal bandwidths and display gains, although a continuous visual display yielded superior performance. Bliss et al (1966b, 1967) used similar tactile and visual displays in a single dimension task, and analyzed the results by model-fitting. He found that the tactile display movements caused by the operator were slower than visual, although reaction times with both a tactile and similar visual display were faster than either display alone. Using describing function analysis, he found that with continuous tactile displays the human showed less gain than with visual displays but had the same bandwidth. Hofmann (1968) compared tracking accuracy in a compensatory tracking task with visual, auditory and electrocutaneous displays; great attention was devoted to making the displays "equivalent" by equating perceived magnitudes of signals, coding in the same fashion, etc. His investigation showed that auditory and cutaneous displays were

more effective than the visual display. Hill (1970) found a "ripple" tactual display yielded superior performance to a standard, continuous CRT visual display.

It is appropriate here to enter a caveat. The reasoning behind the choice of "equivalent" displays is apparently that, if the displays are equated in some way, any findings relating to differences between modalities are generalizable in some way. Three comments can be made here. Results of experiments did not conclusively favor one modality over another, which indicates that, at very least, the ordering depends on the type of coding in the display. Second, it is not at all clear that one can truly define in an ad hoc fashion what an "equivalent" display is. Third, surely if the question of relative performance between modalities is asked in an applied context, the question then becomes one of comparison between the optimal or standard displays in each modality rather than between displays that are equivalent. The final choice between displays is one of system requirements rather than of an absolute selection of modality.

In summary, experiments thus far have shown that tactual displays can be used effectively for tracking tasks, and in some circumstances, tactual presentation can yield performance superior to a visual display.

1.3.3.2 Tactile Display Location

Many different parts of the body have been used as stimulator positions: the face, neck, chest, back, arm, wrist, back of the hand and fingers. Although formal comparison across studies is not realistic, the general location of the stimulus set does not appear to be critical. Bliss (1967) compared single axis tracking with the same display stimulating either the palmar side of the hand or the forehead, and found performance to be unaffected by location. Hill (1970) varied the position of the two stimulators he was using for display and found that, over a variety of positions, tracking performance was not significantly affected by location; the locations did rank order in performance as follows: stimulators attached one to each arm yielded the best performance, followed in order by two fingers, one fingertip, the forearm, and upper and lower left arm.

For any chosen location, however, one must pay attention to the discriminability between stimuli at the various display locations. This should take into account two-point discrimination thresholds, etc. For example, the confusion subjects experienced in two-dimensional tracking that was found by Hirsch and Kadushin (1968) can be probably attributed in part to the lack of discriminability between the stimuli applied to the thumb and forefinger.

Selection of body locations previously used appeared to be based on ease of accessibility and social acceptability (without requiring removal of much clothing). Only two studies (Geldard, 1959; Durr, 1961) have attached stimulators to the large skin areas associated with the torso so as to allow maximum spacing and hence spatial discriminability between stimulators although work at Pacific Medical

has required subjects in one system to rest their back against an array of stimulators fixed to a chair back and in another to apply an array of electrotactors to the abdomen. In the classic studies of Geldard (1959), the vibrators were attached to the chest and Durr (1961) also used the chest. Either the back or the chest would appear to have the same advantages: spatial discriminability, relatively homogeneous surface, and relatively smaller changes in properties during changes of position in the body.

1.3.3.3 Type of Stimulation

Three different types of stimulation have been used in tactical tracking studies: mechanical vibrators, electrocutaneous, and air-jet pulses.

Electrocutaneous has been used relatively infrequently (e.g., Hofmann, 1968; Schori, 1970). The cutaneous sensation is very dependent on the nature of the electrical contact between the skin and stimulator. The range of stimulus magnitudes that can be used between absolute threshold and those levels at which pain is experienced is quite small. The type of sensation experienced depends greatly on the location of the contactor. However, work on this type of stimulation continues at some institutions (e.g. Pacific Medical) and it cannot be dismissed as a possible stimulation type.

Air jet pulses have been favored as tactile stimuli by several investigators recently (Bliss et al, 1966a, 1967; Seeley and Bliss, 1966; Hill, 1970). The advantages of air jet stimulation are that relatively uniform stimulation can be produced over non-uniform cutaneous surfaces and that the arrangement of the stimulators can be easily adjusted. Its disadvantage is relatively difficult instrumentation, which would be particularly true in a rapidly changing altitude environment.

Mechanical vibration has been most widely studied since Geldard (1959) showed that this form of transduction can be used by the human to accept relatively high information input rates. It can afford a simple means of supplying tactual stimulation. Electromechanical tactors can be made smaller than bimorphs, but dissipate power which can cause a temperature rise problem when used for long periods.

1.3.3.4 Frequency of Stimulation

A relatively wide range of vibration frequencies can be used for coding a tactile display. Rogers (1970) has shown that, for recognizing spatial arrays, the highest frequencies tested (160 Hz) yielded best performance. On the other hand, Talbot et al. (1968) suggest that the greatest sensitivity to vibration has been in the 200 to 300 Hz range. In order to deliver suprathreshold stimuli with minimum power requirements, it would be advantageous to operate stimulators in this frequency range. On the other hand, the same authors report that a different frequency range appears to be best for spatially localizing stimuli. Subjects

report the loss of this ability as the frequency is raised above 40 Hz. For high frequencies, there is reported a deeper, more diffuse "vibrating" sense. Thus, for optimum perception of spatial information, the frequency should be low, perhaps 20 to 40 Hz. Hahn (1968) has isolated two tactile systems for the human finger corresponding to these two ranges of stimuli.

Thus, the choice of stimuli frequencies represents a trade-off depending on the relative importance of spatial localization.

1.3.3.5 Stimulus Coding

A number of different stimulus dimensions have been used to code stimuli. Geldard (1959) first used several in combination to allow high information transmission rates to the human: frequency, pattern, duration and location. Intensity is not a good coding dimension because sensitivity to amplitude differs over areas of the body and suffers with adaptation.

Some factors relating to coding of displays has emerged recently from the literature. Eijkman (1970) found that, with a tactile display on the forehead, subjects could track tactile stimuli in the horizontal axis very well, but that the vertical position was imperfectly perceived by the subject. The vibrating contactor was felt quite clearly, but it was the sensitivity for position (below or above the center point) that was poor. This indicates the importance of appropriate spatial localization when spatial coding is used.

Use of the inter-stimulus intervals of 50 to 100 msec (Sherrick and Rodgers, 1966) has shown that the phi (apparent movement) phenomenon exists in the tactual sense as well as the visual. However, it does not appear to be an important factor in the coding of displays. Those authors who have studied the effect of apparent movement on the display have not found any enhancement of performance (Hill, 1970; Howell and Briggs, 1959).

The use of mechanical or electrical stimulators means essentially that tactual displays are quantized. However, there is an interaction among multiple stimuli; perhaps this occurrence can be exploited to provide a continuous display. The phantom-sensation phenomenon has been discussed by several investigators (Alles, 1970; Békésy, 1959). Two equally-loud stimuli presented simultaneously to adjacent locations on the skin may not be felt separately but may combine to form a sensation midway between the two stimulators. This phantom sensation is affected by separation of the stimuli, their relative intensity and temporal order. In some respects, it is often described as the tactile equivalent of directional hearing, although more affected by relative amplitude than phase. By varying the relative characteristics of the two signals, the sensation can be made to move continuously between the two tactor positions. Further related work has been reported by Geldard and Sherrick (1972).

1.3.3.6 Display-Control Compatibility

The importance of the factor of compatibility is illustrated by the results of Weissenberger and Sheridan (1962) who found that better tracking performance was obtained when information was sensed at the location where the manipulated object is grasped rather than at a separate location. Apparently, in this case, the translation of signals into motor actions was in some sense optimal. Considerations of coding tactually should take into account the compatibility with the controls. The optimal display format and relationship to the controls need not necessarily correspond to that which is best for a visual analog. Further, the coding should minimize figure-ground confusion and the possibility of perceptual errors (reversals, etc).

1.3.3.7 Masking and Adaptation

Effects of masking should be considered before selecting a particular display. A number of authors have referred to both intra-sensory and inter-sensory interactions (Vernon, 1953; Alluisi et al, 1965; Geschieder and Niblette, 1967; Gilson, 1969a, 1969b). Although the literature does not allow one to make specific statements, it is clear that the possible effects of masking should be explored when evaluating the design of a display. However, the literature does not suggest that any significant anomalous effects occur.

Adaptation effects do occur in the tactual modality, and adaptation with steady pressure to the skin is apparently more marked than that found in vision or audition. However, mechanical vibration (or other dynamic means of stimulating the skin) apparently demonstrate only a slow increase in threshold value when vibratory stimulation is continued for a significant period of time (Geldard, 1940). Also, in displays such as we are considering here, no single stimulator is likely to have a significant proportion of on-time. Adaptation is very unlikely to be a factor of any significance in dynamic tactual displays. Nevertheless, because of the slow change in sensitivity, coding by intensity is not desirable.

1.3.3.8 Other Relevant Variables

A number of other factors relevant to the design of a display are considered in the literature: the effects of vibrator area (Verrillo, 1963), handedness of the operator (Weinstein and Sersen, 1961), temporal summation (Verrillo, 1965), and time-sharing (Brown et al. 1965; Fransen, Markowitz and Swets, 1968) constitute a representative list.

SECTION 2

INITIAL SELECTION OF DISPLAY PARAMETERS

The program objective is to design, fabricate and evaluate a multi-axis tactile display utilizing present state-of-the-art tactor technology. There are two basic methods of simulating the sense of touch, mechanical vibration and electrical excitation, both of these methods have been explored relative to their methods of coding and their limitations. The arrangement of the tactors to form a display capable of properly communicating the desired information is no less important than the selection of the tactors. Display parameters such as physical size, power dissipation, safety, data update rate, dynamic range have been integrated with the information requirements of error magnitude and direction and error rate to generate an optimum display format for tactile aircraft control.

2.1 TACTORS

The cutaneous stimulator (tactor) requirements for this program exceed those normally sought for most applications. Most work has been associated with applications wherein the tactile display is the primary data channel, hence the required tactor stimulation magnitude has to only be high enough to provide reliable perception. In this program the visual sense remains the predominant or primary data channel and the tactile display information must compete with this "noise" and be perceived. Our quest for tactors has focused on obtaining one which will provide a strong enough stimulation to be sensed in the presence of additional inputs to other modalities, yet small enough to be adaptable to a multiple-element-display. Stimulators such as Bice's vibrator, Sherrick's vibrator, permanent magnet solenoids, piezo-electric bimorphs, and electrodes of various types had been considered, but only electrotactors and bimorphs were explored to any degree.

An electrotactor, similar to those utilized by Collins and Saunders (1970) was tentatively selected and has received our prime emphasis due to its obvious superiority in such parameters as size, weight, power required, and data rate. Subsequently it was decided to construct a number of large bimorph tactors in a parallel development since the electrotactor did not appear to be entirely "comfortable" to all the investigators using it. Subjective sensations of those experimenters (30% of the total) are described as a mild stinging or burning.

Tactor parameter comparisons are shown in Table 2-1 for the tactors that we have evaluated. The information is tabulated to provide a direct comparison of some of the important parameters of the tactors. Figure 2-1(a) illustrates the tactor excitation necessary to obtain satisfactory stimulation levels. When an array of tactors are used, the excitation period of an individual tactor should be as short as possible so as to maximize the potential data rate of the display.

2.1.1 ELECTROTACTORS

Electrotactors stimulate the sense of touch by short duration, constant current pulses through the skin. Our work in this area has been to vary the electrical and physical parameters to obtain a maximum comfort-intensity level, i. e., a stimulation that is well above threshold but yet entirely acceptable or comfortable. Quite a bit of experimental work has been done in this area, but much of the prior experimentation employed a single conductor electrode with a large return plane at a remote location on the body. This type results in through-body-conduction which we considered objectionable for an array using a large number of tactors. Guided by the work of Gibson (1968), Saunders and Collins (1970, 1971), we fabricated and evaluated a number of different coaxial electrodes which are described in Table 2-2 and Figure 2-2.

Skin preparations of saline solutions and alcohol were investigated with the result that alcohol by itself appeared the most effective. Cleaning the skin prior to applying the tactors minimize the time required to adapt to the electrotactors.

Three A type tactors were the first fabricated because of the immediate availability of the material - BNC connectors and silver epoxy. All other tactors were fabricated using sterling silver electrodes.

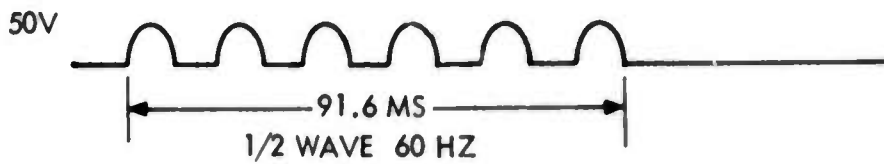
Tactors B, C, and G operate identically for the most part except that two subjects stated Tactor C was more comfortable than Tactor B. Tactor G differs from C only in the annular insulation width; it has 1.2 mm, while C has 0.7 mm. This made no perceptible signal or sensation difference.

Tactor F was the first major departure from the geometry of the initial tactors. It has a small 1/16 inch diameter center electrode and the annular space between the inner and outer electrodes was not filled with epoxy. As expected, the touch threshold level was less than that required for larger electrodes. The initial sensation appeared more sharp, but when stabilized, the sensation intensity can be adjusted to the same levels as experienced with the 5 mm diameter electrodes except less current is required.

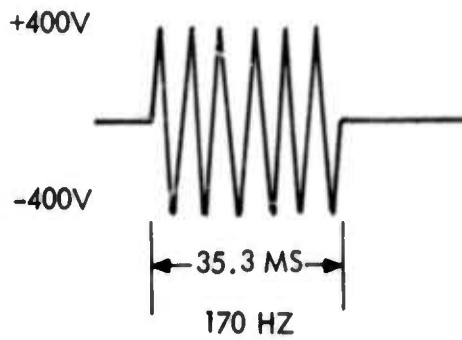
Tactor E was fabricated with the hope that the larger area would provide a stronger, yet comfortable signal; as it turned out though, the same "comfortable-sensation-intensity" was reached at the price of higher peak current. About 10 ma were required to create an intensity equivalent to a 5 ma sensation with the smaller tactors.

TABLE 2-1
TACTOR PARAMETER COMPARISONS

Parameter	Vibrotactile			Electrotactile Coaxial-Bipolar
	PM Electromagnetic	Piezoelectric		
1. Size	13 mm OD X 65 mm Long 2 mm tip	43 mm X 19 mm X 7 mm 1 mm tip		11 mm OD X 3 mm
2. Power, Average Continuous	1.7W (50V sq wave)	1.7 Volt-Ampere (0.67 mfd)		4 mW
3. Tactor Period 6 Pulses	92 ms	35 ms		24 ms
4. Pulse	1/2 wave, 60 Hz	Sine Wave, 170 Hz		50 μ s nom. at 250 Hz rate
5. Supply Voltage	50V	150 Vrms		150V
6. Tactor Voltage	50V	150 Vrms		80-40V at 2-6 ma
7. Tactile Sensation	Limited	Limited		Can be adjusted for levels well above threshold
8. Safety	Safest - lowest supply voltage	Highest supply voltage		Moderate - safer than bimorph
9. Array Fabrication	Bulky, but mobile use possible	Bulky, but mobile use possible		Mobile, requires good skin contact
10. Special Problems	Tactor Cooling Plunger Demagnetization Finite Life	Difficult mounting structure Finite Life		Warmup required Perspiration Variable threshold Comfort factor - temperature and relative humidity Psychological
11. Operational Mode	Plunger pokes skin	Plunger pokes skin		Constant current capacitor discharge through skin

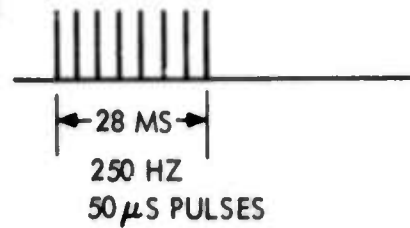


PERMANENT MAGNET VIBROTACTOR

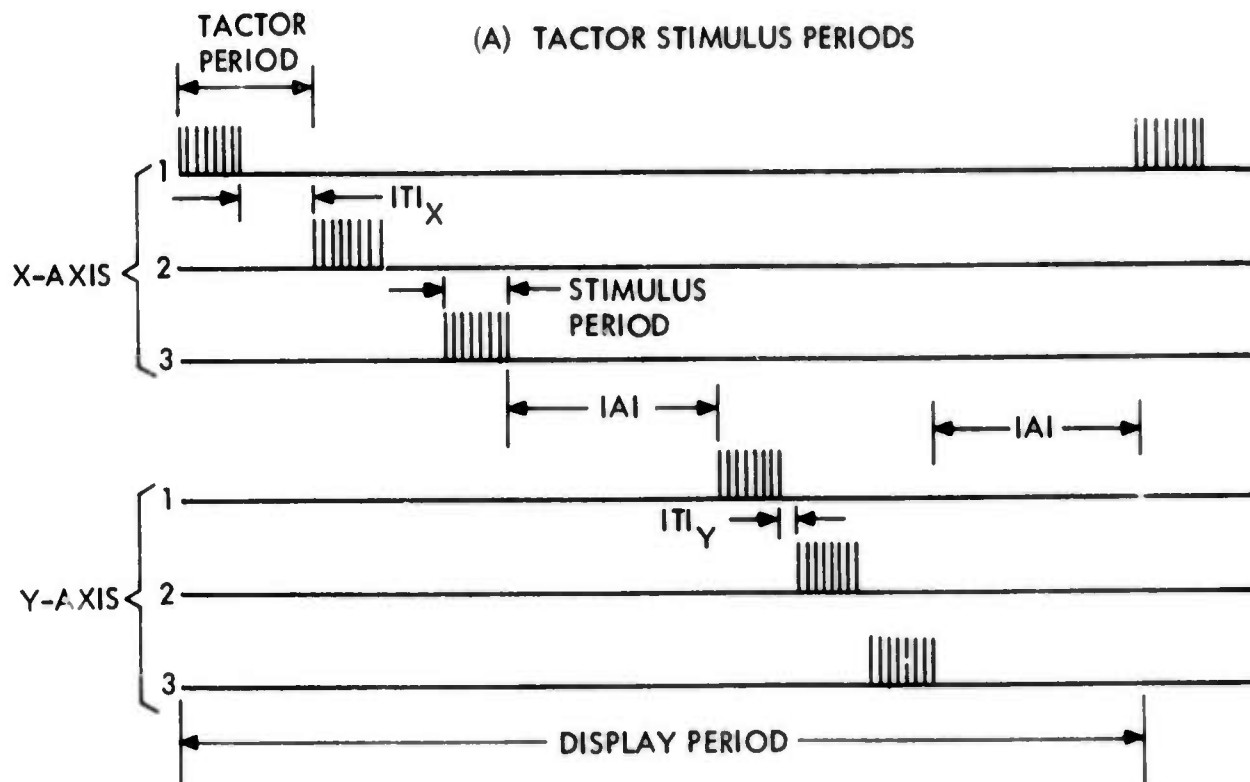


BIMORPH VIBROTACTOR

2-7 MA



ELECTROACTOR



(B) TACTOR ARRAY DISPLAY PERIODS

Figure 2-1 Tactor Stimulus and Display Periods.

TABLE 2-2
ELECTROTACTOR TEST MODEL PARAMETERS

Tactor	Material		Inner O. D. mm	Elect. Area mm ²	Insul Width mm	Outer O. D. mm	Elect. Area mm ²	AOE/ A _{IE}	Surface ¹	Touch ² Threshold ma
	Electrode	Insul.								
A	Sil. Epoxy	Lucite	5	20	1.0	11	48	2.4	Dome/Flat	2.0
B	Ster. Sil.	Epoxy	5	20	0.7	10	52	2.6	Dome	2.0
C	Ster. Sil.	Epoxy	5	20	0.7	11	63	3.6	Dome	2.0
D	Ster. Sil.	Epoxy	5	20	2.4	14	80	4.0	Dome	2.5
E	Ster. Sil.	Epoxy	9.9	77	3.5	29	442	5.6	D _{IE} /F _{OE} ³	3.5
F	Ster. Sil.		1.7	2.26	2.3	10	52	23	Dome	1.0
G	Ster. Sil.	Epoxy	5	20	1.2	11	53	2.6	Dome	2.0

¹ Dome: About a 22 mm radius.

² Location: Abdomen - 13-16 cm to right of navel.

³ Inner Electrode: Dome, outer electrode flat.

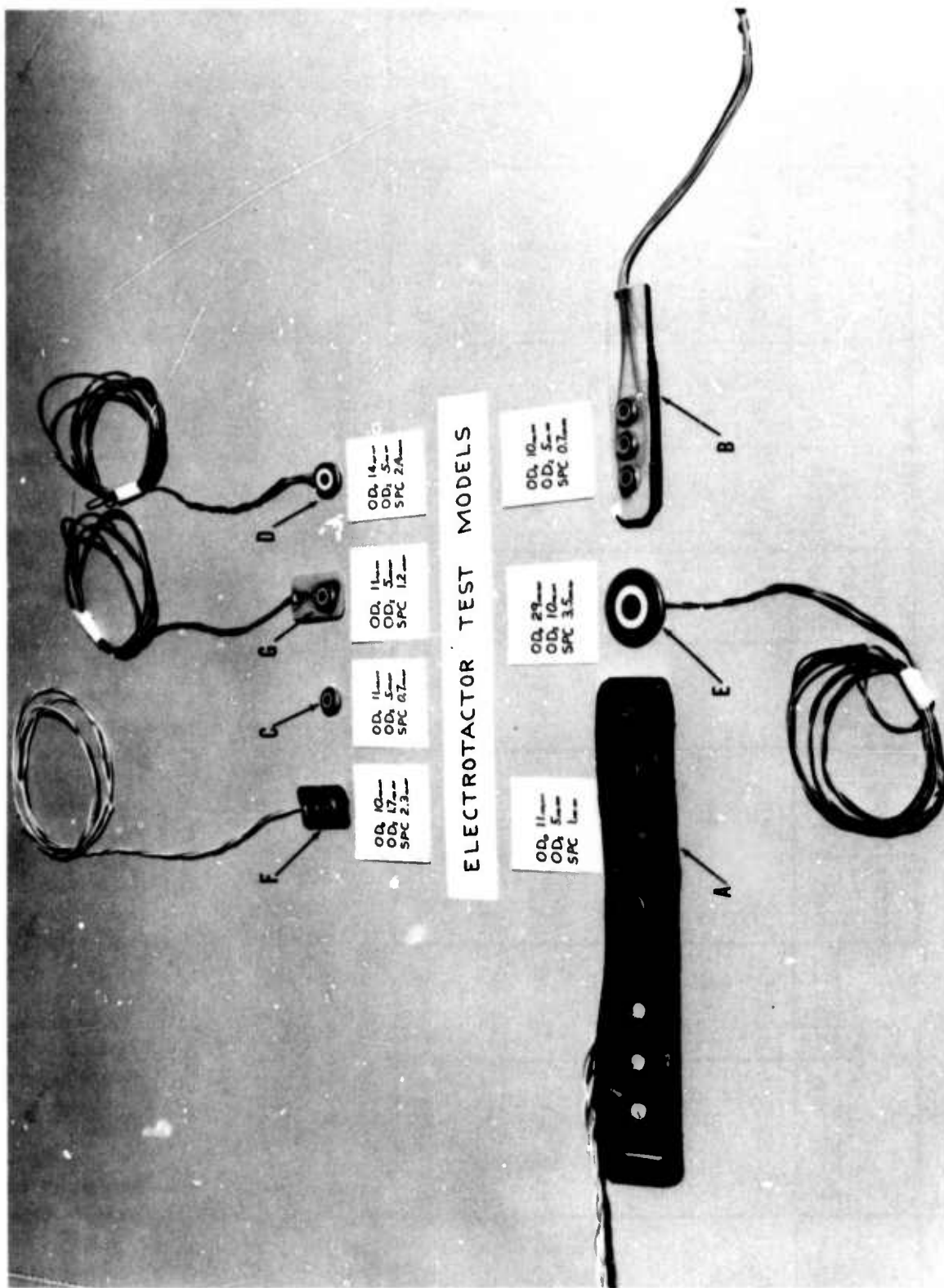


Figure 2-2 Electrotractor Test Models.

Tactor D was fabricated to test whether or not the insulation width had any major effects on operation. There may be some minor effects, but for our purposes it produced the same intensity. What all this means is that the single tactor comfort/intensity level cannot be increased by varying tactor geometry and drive signals, but can be reached by a suitable selection of these parameters.

It was observed that threshold current and maximum comfort current are not directly proportional to electrode area. This is probably due to the edge effect wherein the electrode peripheries bordering the insulating annulus have a greater current density than the balance of the electrode areas and the sensation level is proportional to current density.

Minimal data were taken to arrive at the threshold levels listed in Table 2-2. All the data were taken by a single experimenter.

The final tactor geometry selected for application to the arrays was type A, made with sterling silver electrodes and LCA-4 as the insulator; the total thickness of the tactor is around 2.6 mm.

2.1.2 VIBROTACTORS

Vibrotactors stimulate through skin contact with a vibrating element; common forms are electromagnetic, piezoelectric, and pneumatic. The electromagnetic tactor can be designed to exceed the required force-displacement threshold anywhere on the body (pneumatic and even hydraulic tactors also share this freedom). They are bulky and adaptable most readily to fixed installations, such as chairs. One of the best electromagnetic tactors known at this time is the one designed by Holmlund and Collins (1970). It is 65 mm long, 13 mm in diameter, and uses a domed 2 mm diameter tip to poke the skin. It is a solenoid with a permanent magnet armature. With 30 to 50 volt peak, half sine wave, 60 Hz pulses, it easily exceeds touch threshold.

The air gap solenoid can also be used as a stimulator, but it too requires a relatively long excitation period. Figure 2-3 shows the two types of electro-mechanical tactors evaluated and rejected as possible tactors for display application.

Initial interest in the bimorph as a vibrotactor element was stimulated by exposure to the Opticon (Telesensory Systems, Inc.), an optical-tactile reader for the blind. The Opticon utilizes an array of 144 bimorph driven probes as a single finger-tip display. The finger has high tactile resolution and low touch threshold levels allowing the use of small bimorphs. Since we are restricted to

SOLENOID VIBRATORY TACTORS



PERMANENT
MAGNET

AIR
GAP

Figure 2-3 Electromechanical Solenoid Vibrators.

other parts of the body where threshold levels are higher, we obtained some larger bimorphs and evaluated them using the 3 tactor linear array illustrated in Figure 2-4.

The results were encouraging and using the work of Holmlund and Collins (1970) and Verrillo (1963) a yet larger bimorph 0.75×1.75 inch was specified and a number were procured to fabricate the desired displays. An exploded view of one vibrotactor shown in Figure 2-5. The steel tubing is encased with shrink tubing providing an insulated one mm skin probe. Each bimorph tactor was assembled as an individual unit for greater display flexibility. The nonloaded probe projects .020 inch above the surface of the tactor to allow preloading when the tactor is placed against the skin. The raised portion of the tactor surrounding the probe insures skin contact and provides damping to eliminate much of the vibration wave effect. The bimorph is driven with a 6 cycle burst of 170 hertz, 150 volt rms power. The resonant frequency of the bimorph and its probe is around 120 hertz. Operation at resonance was not explored because of deflection snubbers which would be required, also the higher frequency allows a better signal margin above threshold. Beyond 170 hertz, the operation of the bimorph degrades too much for good stimulation levels. While the bimorph is large, it has the advantage of being available and does not dissipate power as it is almost a pure capacitor.

2.1.3 TACTOR EXPERIMENTS

The tactor experiments were formulated to determine the boundary limits of the various tactor excitation and display parameters such as pulse width, peak current, pulse repetition frequency (PRF), inter-stimulus interval (ISI), etc. Even though most of these data were available from our literature search, some preliminary experimentation was necessary before the final display system was designed. The abdomen was selected as the most likely site for the display. The back was tested but with its higher touch threshold and physical nonuniformity it was bypassed as a location for this evaluation program. The arm was also tested but it proved to have characteristics unsuitable for tactile arrays.

2.1.3.1 Single Electrotactor

The initial experiments involved only one tactor in order to identify the electrocutaneous sensation. The constant current drive circuit used for this program was designed by Dr. C. Collins, and selected for its simplicity. An HP214A pulse generator and a G.R. Model 1396B Tone Burst Generator were used to generate the excitation pulse groups and the inter-stimulus interval (ISI). The circuit schematic is shown in Figure 2-6. With this equipment, the pulse width, pulse frequency, number of pulses, and ISI can be independently controlled. In the quiescent mode, transistor Q1 is on and Q2 is off and capacitor C, is being charged by the 150 volts through R2, the skin, and R4. Resistor 4 is added only for current monitoring. When Q1 is turned off, voltage is applied to the base of Q2 turning it on, hence its emitter is at the clamp voltage V_c less the apparent transistor E-B

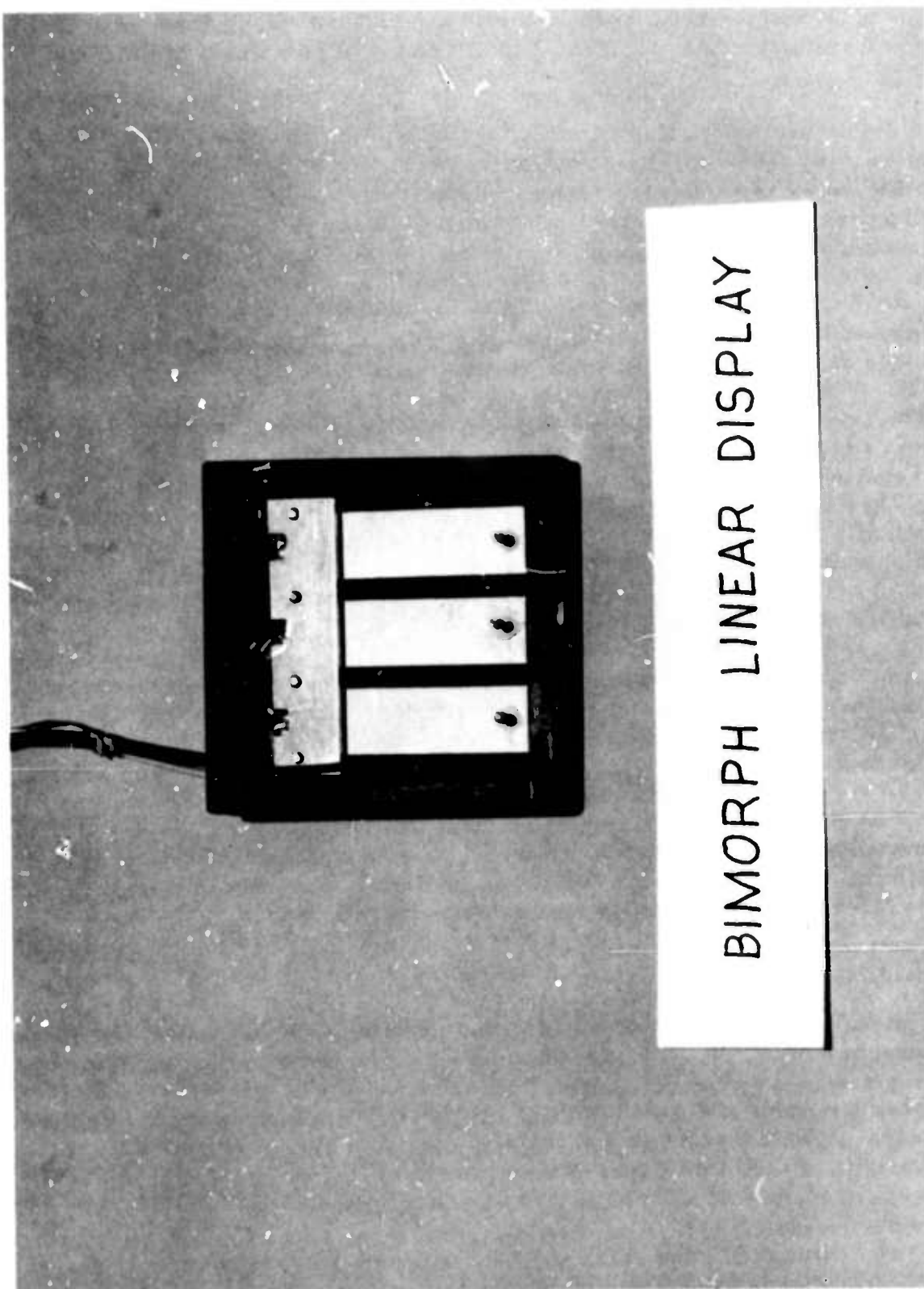
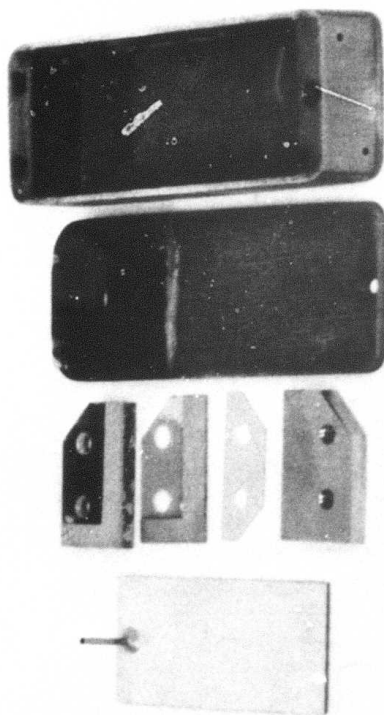


Figure 2-4 Bimorph Vibrotactor Array.



BIMORPH TACTOR



Figure 2-5 Exploded View of the Bimorph Vibrotactor.

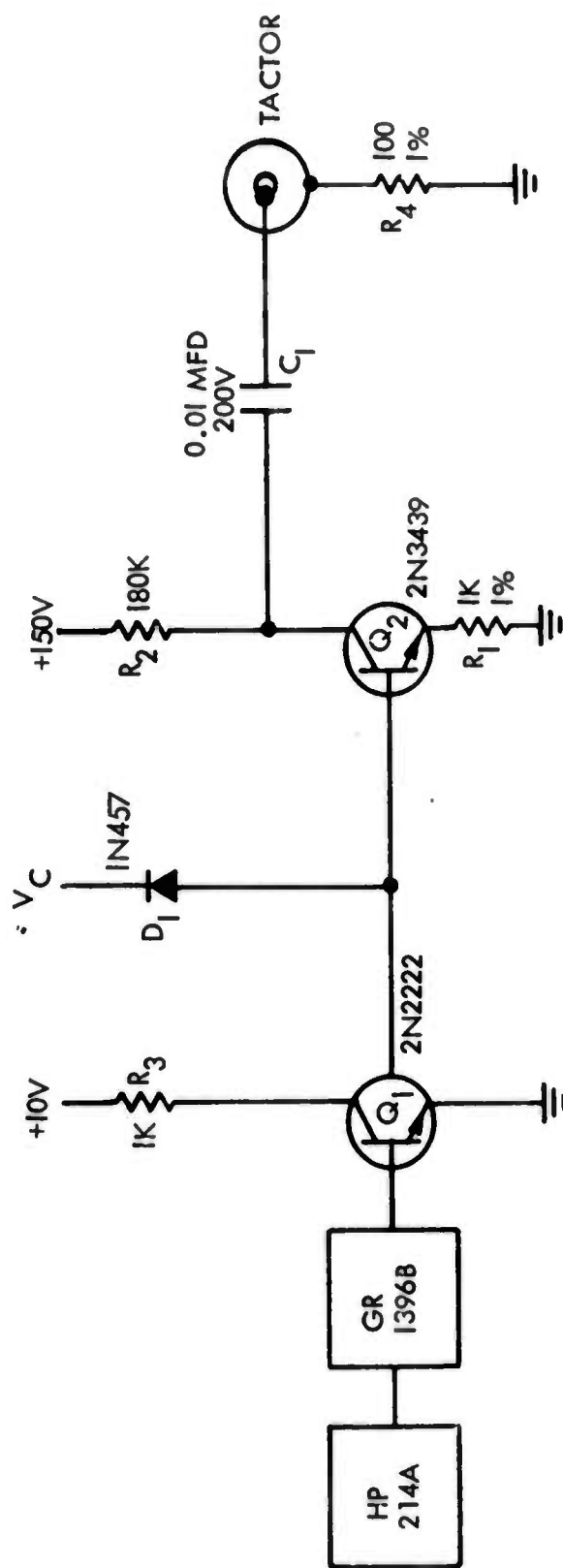


Figure 2-6 Single Tactor Evaluation Circuit.

voltage. Since the emitter voltage must follow the base voltage, the current through R_1 and Q_2 will be directly proportional to V_c . The clamp voltage is adjusted to obtain the desired constant current through the skin. The signal current through the skin originates from the charge on capacitor C_1 ; essentially, C_1 is discharged at constant current through Q_2 , R_1 , and the skin for the period of the signal pulse width.

The arm was surveyed as a possible location for the tactors, however, it was quickly found inadequate for electrotactor stimulation. There are numerous locations where the electrical stimulation causes throbbing throughout the forearm; then with the tactor moved laterally about 1 cm, the threshold was so high that the sensation could hardly be felt. For this reason the arm was rejected as a possible location for a multitactor array.

The finger tips; as sensitive as they are to mechanical vibrations appeared to have little sensitivity to the coaxial electrotactors.

The tactor was then placed on the abdomen for the test. With a 500 pulse per second (pps) train of four 100 microsecond pulses and an ISI of 1 second, threshold was reached at 2 ma, with 5-6 ma creating a feeling well above threshold, analogous to a buzzing pencil poke. No burning or stinging sensation was present. Other observations are as follows:

- a. A single 6 ma pulse feels much like four 2 ma pulses.
- b. A train of 8, 6 ma pulses feels more intense than 4 and also the length of excitation period can be discerned.
- c. Pulse trains of 16, 32, 64, and 128 pulses are not painful at 6 ma.
- d. Decreasing the PRF from 500 to 200-250 did not appear to decrease the touch threshold - no difference in signal level was noted at all.
- e. With a 1000 Hz PRF, the sensation is quite degraded.
- f. Increasing pulse width increases intensity.
- g. As the ISI is decreased from 1 to 0.1 second, the magnitude of intensity of the sensation decreases. This appears to be mostly adaptation for when ISI is quickly changed to shorter periods, the initial intensity appears the same as for longer dwell time, but it then decays.
- h. With a continuous 500 Hz PRF, 100 microsecond pulse width, 4 ma current, the skin feels warm.
- i. With the initial pulse train of 4, 500 Hz pulses applied to the back, the level of sensation appears less than for the abdomen; furthermore, the sensation

is sharper to the extent that in some places it is more of a stinging rather than a buzzing sensation. Current level had no control over the type of sensation, only intensity.

j. The peak voltage across the skin was 90 volts for the first pulse and 70 volts for the fourth pulse. (In the longer pulse trains, the amplitude sequentially decreased.)

k. With a single pulse and an ISI or around 1 second, the sensation for pulse widths between 100 and 600 microseconds appeared the same.

Based on these initial observations the electrofactor was judged as a very good tactile stimulator suitable for further tests using 3 tactors which could be sequenced in either direction. The abdomen was selected as the optimum area for the electrocutaneous display.

2.1.3.2 Multiple Tactor

These experiments utilized a linear array of 3 tactors to observe the effects of data rate and multiple-tactor excitation. When using a single tactor, the term ISI has been used to define the interval between stimulus periods. Figure 2-1 illustrates the stimulus period and other related time intervals of tactor displays. To avoid confusion and to eliminate dual usage of ISI, dwell periods relating to multiple factor, single and multiple axis displays are defined as follows: Intertactor interval (ITI) is the time between the stimulus termination of one tactor and the stimulus initiation of an adjacent tactor. The stimulus period plus the ITI equals a tactor period. Interaxis interval (IAI) is the time between stimulus termination of the last tactor of one axis and the stimulus initiation of the first tactor of the same axis or different axis. Display period is the interval between the start required for one complete cycle of data presentation. The same pulse generator and tone burst generator were used to form the pulse groups and the intertactor interval (ITI). Additional logic circuitry was added to sequence the pulse groups from one tactor to the next in either direction. The sequences were repetitive with the interaxis interval (IAI) between the last and first tactor of the sequence being twice the ITI. Each tactor had its own drive circuit, the same as shown in Figure 2-6 except 0.02 mfd capacitors were used. The charge of the 0.01 mfd capacitor was too limited.

For this series of experiments, the following initial conditions were used:

Tactor: Type A

Tactor Spacing: 0.75 inch

Location: Abdomen - right side, just below ribs with tactor #1 on the left

Pulse Width: 100 microseconds

Pulse Frequency: 500 Hz

Pulses in Group: 4

Peak Current: 5 ma

ITI: 250 ms

The initial test of the linear array was a bit surprising, the perception of 3 sequenced tactors was impossible, the sensation felt like a blur over the whole tactor area. Confidence of proper tactor operation was restored with the use of an oscilloscope. The ITI period was increased to 500 ms and the 3 tactors were resolved, then with ITI back at 250 ms, they remained as individual stimulations. These observations occurred only once, during the initial experiment, subsequent trials provided tactor resolution immediately upon turn-on demonstrating that there is an initial learning requirement.

Once the tactor array perception was established, an experiment was conducted to determine the directionality limitations of a two tactor sequence. With the 250 ms ITI, a 750 ms dwell period existed between the two tactor sequence. The direction of the sequence was easily identified along with the knowledge that two tactors made up the sequence.

When the ITI is decreased to about 100-150 ms, the perception of the stimulation is that of one long burst, upon concentration, two separate signals can be identified but direction is lost.

With dwell time set back to 250 ms, increasing the number of pulses from 4 to 8 increases the intensity of the signal, but tends to blur the individual perception of each tactor stimulation. When switching back to four pulses, it felt as though the threshold level had increased (effect of adaptation).

Increasing pulse width from 100 to 150 microseconds changes the feeling from a tap to a short sting or pin prick while decreasing pulse width just decreases intensity. Next the first and third tactors were energized with the third tactor being excited with the second signal of the sequence. This allowed the same electrical timing as with tactors 1 and 2, but with a 1.5 inch spacing between the tactors. With the original excitation signals, the direction of the sequence is very clear. When the ITI is reduced to 100 ms, the sequential direction is lost but the perception of two distinct signals remain. With 8 pulses instead of 4, direction remains discernible. Increasing the length of the pulse train or the number of pulses appears to give the illusion of a larger stimulation area.

Now all three were spaced 0.75 inch apart and connected in their proper sequence. With the original excitation signals, the sensation is not too clear. It felt as though the first two tactors are at the same location and the third tactor definitely displaced from the second. Upon concentration on the signals, a distance between the first two signals is perceptible; however, the sensed distance between the second and third signals appears two to three times the distance between the first and second. With the ITI increased to 500 ms, directional perception is very strong. It appears that the higher data rates related to the 250 ms ITI tends to cause some level of adaptation because the sensed signal strength is less than when the ITI is 500 ms. Consider here that with a ITI of 250 ms, an individual tactor is being excited once a second.

With 8 pulses and a 500 ms ITI, the directional sense is very strong. Decreasing the ITI to 200 ms wipes out the data and the sensation becomes a little uncomfortable.

The three tactors were now mounted vertically on the abdomen in about the same general location. With the original signals, the perception was the same as before except the sensed distance between the tactors appeared the same.

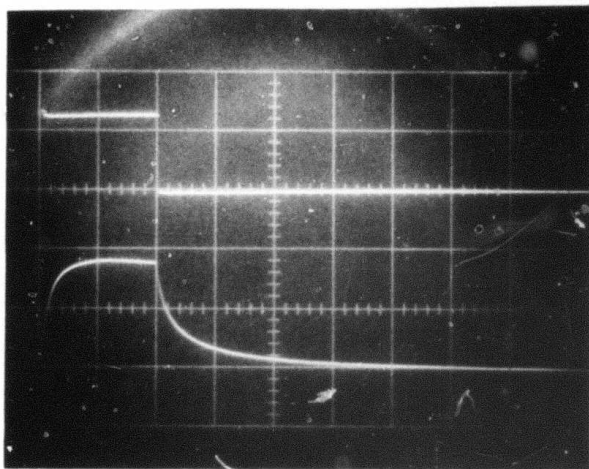
The three tactor array was then located on the back with tactor No. 3 closest to the spine. The perceptible effects were the same as for the tests on the abdomen, except for the following observations:

- o Threshold appeared higher, thus 150-200 microsecond pulse widths were used to obtain usable signals.
- o Threshold level seems to decrease as the spine is approached.
- o The perceptual distance between tactors 2 and 3 appears shorter than between 1 and 2.
- o Sequence direction was identified with dwell times down to 175 ms.

The tactors were now remounted on one-inch centers and attached again to the original abdomen location. The only deviation from the original data was that the sequential direction was detectable down to ITI values of 150 ms; at 100 ms direction was lost.

2.1.3.3 Polarization Effects

The effects of polarization or the ionization of the skin can well be a study in itself and was not considered as part of this program, however, one can hardly turn on an electrotactor and not make some observations. The capacitive discharge drive circuit selected for this program has constant current pulse control with one voltage polarity, hence it can be termed a monophasic drive. However, consider the coupling capacitor from which the skin current is derived; when not supplying the pulsed current, it is receiving renewed charge from the 150V power source, and through the same skin area through which it had been discharged; consequently equal charge has flowed through the skin in both directions. This can be seen in Figure 2-7(b) by observing the skin voltage negative undershoot at the trailing edge of the excitation pulses. The vertical scale of this photo is such that the positive peak amplitude is not presented. The action of the capacitive coupling in a pure sense makes the drive circuit biphasic in nature but since there is little current flow during this period, the effect is not the same as would be experienced with a true biphasic drive. The skin however cannot be modeled with fixed, passive parameters such as a resistor and a capacitor. Its electrical parameters appear to change as a function of current, or the rate of charge as a function of time, thus the capacitor discharge drive is somewhere between monophasic and biphasic.

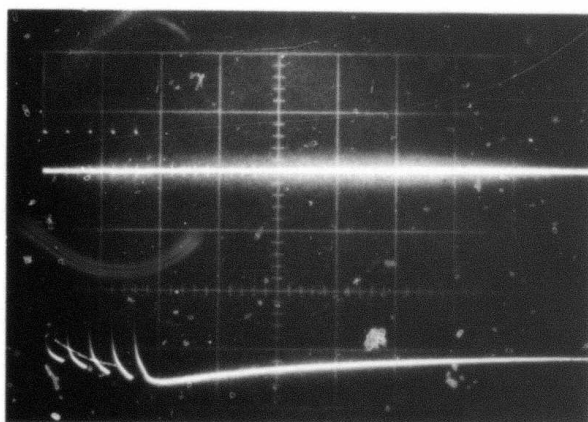


TOP: SKIN CURRENT
5 MA PER CM

BOTTOM: SKIN VOLTAGE
50V PER CM

TIME BASE: 50 μ S PER CM

A) SINGLE PULSE, TYPE G TACTOR



TOP: SKIN CURRENT
5 MA PER CM

BOTTOM: SKIN VOLTAGE
20V PER CM

TIME BASE: 5 MS PER CM

B) MULTIPLE PULSES, TYPE G TACTOR

Figure 2-7 Skin Stimulation Electrical Signals.

The first effects attributed to polarization is the warm up time or break-in period necessary for the electrotactors. When a linear array, or a single tactor is driven by a continual train of pulse groups, the initial sensation is sharp, then in about 3-5 minutes the sensation settles to one of vibration. During this period, the skin impedance is being changed until some asymptotic value is reached. This final value to some extent seems to be controlled by both the average and transient characteristics of the electrical drive signal.

During the warm-up period, the dynamic resistance of the skin decreases. Repeated observations with a type G tactor on the abdomen showed a peak voltage drop from about 85 volts to about 60 volts in this period with a constant current of around 5 ma. The rise time of the voltage is of course affected by the effective skin capacitance. The voltage wave form as shown in Figure 2-7(a) was usually flat after about 50 microseconds, but at times was observed to have a definite negative slope after the initial 50 microseconds.

A conclusion drawn from this experience is that some polarization is helpful to electrocutaneous stimulation; it appears to reduce the acuity of the nervous response.

Adaptation and polarization may affect the short-term perception of the tactile stimulus. As a possible method for the prevention of the effects of these phenomena, electrode polarity reversal was tried. A type G tactor was wired to a double pole double throw reversing switch and positioned 11 cm to the right of the navel. For the initial turn-on, a control tactor was located 5 cm to the left of the test tactor and it was excited prior to the test tactor. A constant current level of 4 ma was held during the tests. The test-tactor voltage settled to 52 volts with the center minus (-); i.e., the center electrode is driven negative with respect to the outer or ground electrode. The polarity was then reversed, center (+); i.e., the outer electrode is driven negative with respect to the inner or grounded electrode. The voltage immediately dropped to 40 volts and the sensation was barely perceptible - the control tactor functioned normally. Switched to center (-) the voltage jumped to 50 volts and within about a minute reached 52 volts. The initial sensation was as sharp as it is for an initial turn-on, but in this case it lasts for seconds instead of minutes, it then settled to a normal sensation. This sequence was tried a number of times with the same results. The test was continued while moving the control tactor further away until it was located on the left index finger. At this position, center (-) produced 44 volts and good sensation while (+) produced 34 volts and very poor sensation. Without the control tactor, both center (-) and center (+) produced 52 volts, but the sensation intensity generated by center (+) was considerably less than with center (-). The control tactor was then laid aside and a final test was made with the index finger grounded. Center (+) voltage dropped to 22 volts with very little sensation at the tactor and center (-) produced a drop to 40 volts and no loss in sensation intensity.

The loss of sensation intensity generated by an isolated reversed polarity tactor is probably due to the larger negative electrode. It is known that the touch

sensation is mostly developed under the negative electrode, and when area is increased holding current constant, sensation intensity decreases. The further loss of intensity when a remote ground is present can possibly be explained by the induced extended ground caused by body fluids. This would reduce the edge effect explained earlier and further reduce the current density along the inner periphery of the electrode, hence the sensation would be reduced.

The results of this test indicated that coaxial electrodes can only be operated in one configuration and polarity reversal in the manner discussed in this section is not feasible. The control of polarization effects can best be minimized through the use of biphasic constant current drive. Adaptation may not be a severe problem in our displays as they are configured to have no factors on when there are no error signals, hence the null time is available to recover from any adaptation that may have occurred when an error signal was being displayed.

2.1.4 Biphasic Constant Current Drive

Prompted by the general feeling that biphasic stimulation is more comfortable than monophasic, some preliminary experiments were run after the final display system fabrication had been finished. John McCray (1970) followed Gibson's (1968) lead and experimented with 125 and 250 μ s pulses with apparently good results. Our philosophy had been guided by Dr. Carter Collins' work using a number of narrow pulses for each excitation period. This seemed a good choice for our experiments, wide pulses have indicated less favorable operation, consequently our biphasic experiments were based on narrow pulse excitation. Dr. Frank Saunders had just completed some experiments on biphasic stimulation. His work incorporated narrow pulses at a relatively high rate wherein the number of pulses in an excitation period determined the stimulation intensity. An amplitude of 10 ma is used with an initial 10 microsecond pulse width. Pulse width is then increased to achieve threshold, then the number of pulses is increased to the desired stimulation level. The initial results were quite encouraging, but before the effect can be fully evaluated the PRF and delay between the positive and negative pulses will have to have their upper control limits increased.

The most interesting phenomenon is the stimulation cancellation effect. Starting with 20 μ sec pulses alternating positive then negative separated by a 30 μ sec interval, the sensation is comfortable, but not intense. As the interval is decreased, the stimulation intensity begins to fall off at around 15 μ sec, at 10 μ sec and less there is no stimulation at all, it is completely cancelled by the sum effect of the biphasic pair of pulses.

Pulse widths and delays up to 30 μ sec, PRF's of 500-3000 Hz, and 2 to 70 pulses were initially varied during the initial experiments with the following observations. The biphasic drive is more comfortable than a similar monophasic drive, but with the above parameters and using 10 ma peak currents a stimulation intensity equivalent to the stimulation level of 8, 5 ma, 50 μ sec, 250 Hz pulses

was not reached. Greater parameter variation may provide a more optimum combination, however, no further exploration of this effect is scheduled under the present program.

2.2 DISPLAY CONFIGURATION DEVELOPMENT

The required displays must provide information to allow multiaxis dynamic tracking, hence, a minimum of three parameters must be provided to each axis. They are error-magnitude, direction and rate-of-change.

2.2.1 DISPLAY FORMATS

The initial array selected is the "polarized" 3 axis configuration shown in Figure 2-8. The tactor excitation sequence always begins with designated reference tactors; for the X-Y part of the array it is tactor R and for the third axis of the display, the tactors C and C'. The tactor excitation is rippled along the axis in a direction dependent on the sign of the error signal. There are two controlling analog inputs for each axis:

NT is the analog input signal that is quantized to 3 levels, with each level adding one tactor to the excitation sequence.

T is the analog input signal that directly controls the tactor ripple rate.

For example, assume the three axes to be presented are aircraft altitude, heading, and bank angle. The data for each axis will be presented serially and each axis will use the same data-presentation format.

The altitude (deviation from a preselected value) begins with the excitation of the center reference tactor and then sequentially ripples either up or down, depending on the sign of the error signal.

The magnitude of the signal applied to the NT input of this channel determines the number of tactors used to display the data. Depending on the scale factor of the signal, all the tactors can be used in the display of a small error, or for lesser channel gain, the number of tactors will equal the quantized level of error magnitude. A positive error would use part or all of the tactor sequence R, 1, 2, 3. The rate at which the selected tactors are rippled is controlled by the absolute value of the signal applied to the T input. This signal can be proportional to error magnitude or error rate.

Heading errors are processed in an identical manner, but tactors R, A, B, C or R, A¹, B¹, C¹ are used.

Bank angle error is indicated by simultaneously rippling the outside vertical rows starting with C and C¹ as the references. A left bank, for example, where the error magnitude is sufficient to cause all tactors to be energized; the left

vertical row ripples down from the reference C^1 and the right vertical row simultaneously ripples upward from tactor C. As before the ripple rate is proportional to the signal applied to the \dot{T} input.

Our expression "polarized-display" indicates that a tactor-axis is driven bidirectionally from the reference tactor in accordance with the sign of the error.

A "nonpolarized-display", Figure 2-9, does away with the reference tactors and starts a data-strobe from one end (or the other) of a tactor axis and for large amplitude errors involves all of the tactors in that axis. Otherwise the basic strategy is the same as for the "polarized-display". Advantages of the nonpolarized configuration are thought to include:

- o Requires 16 tactors (instead of 25)
- o Better form factor (smaller)

Note that this display as shown in Figure 2-9 has been split to provide the bank function in a separate display from the heading/altitude information. This option may make it easier to locate the three axis display on the subject. For this display, a large left heading error would ripple ABCD and a right error DCBA, and an altitude deviation above the reference altitude would use the sequence 1234, etc.

The final tactile displays shown in Figure 2-10 are capable of presenting any 2 of the 3 axis formats as either polarized or nonpolarized displays using either electrotactors or vibrotactors. The two polarized X-Y displays on the left have fixed geometry, i. e., the tactors cannot be moved. The two arrays on the right are variable geometry allowing variable tactor spacing and format changes. The tactors are held in place with velcro. The two arrays on the right are shown in the nonpolarized X-Y format. Unused tactors are positioned out of the way.

2.2.2 INITIAL X-Y DISPLAY OBSERVATIONS

The polarized X-Y electrotactor display was fabricated and tested in mid-September. These preliminary tests employed only the manual selection of the tactor sequence and the ripple frequency. The array was located on the right side of the abdomen. The excitation of each tactor consisted of 4, 100 microsecond pulses delivered at a 500 hertz rate. The ITI was controllable between the limits of 6 to 120 ms which corresponds to a ripple frequency of 80 to 8 hertz. The minimum frequency of 8 hertz was selected on the basis of maintaining a minimum display period (8 tactor periods) of one second. The dwell time between each axis display was adjustable between 50 and 250 milliseconds.

Relative to a prior experiment where two 3-tactor linear arrays were positioned orthogonally and simultaneously rippled, the indicated direction of the tactor sequence with the present polarized X-Y display was very vivid when 3 or 4 tactors

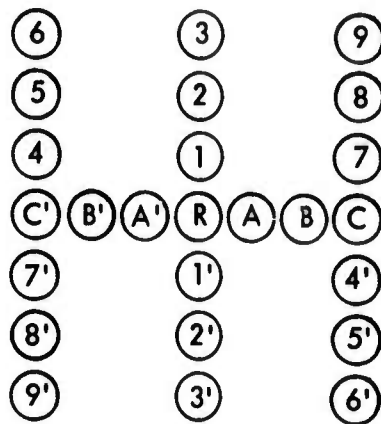
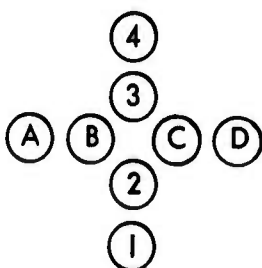


Figure 2-8 Three-Axis Polarized Display Format.

HEADING/ALTITUDE



BANK ANGLE

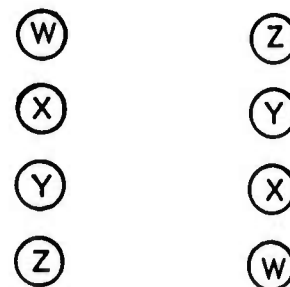


Figure 2-9 Three-Axis Nonpolarized Display Format.

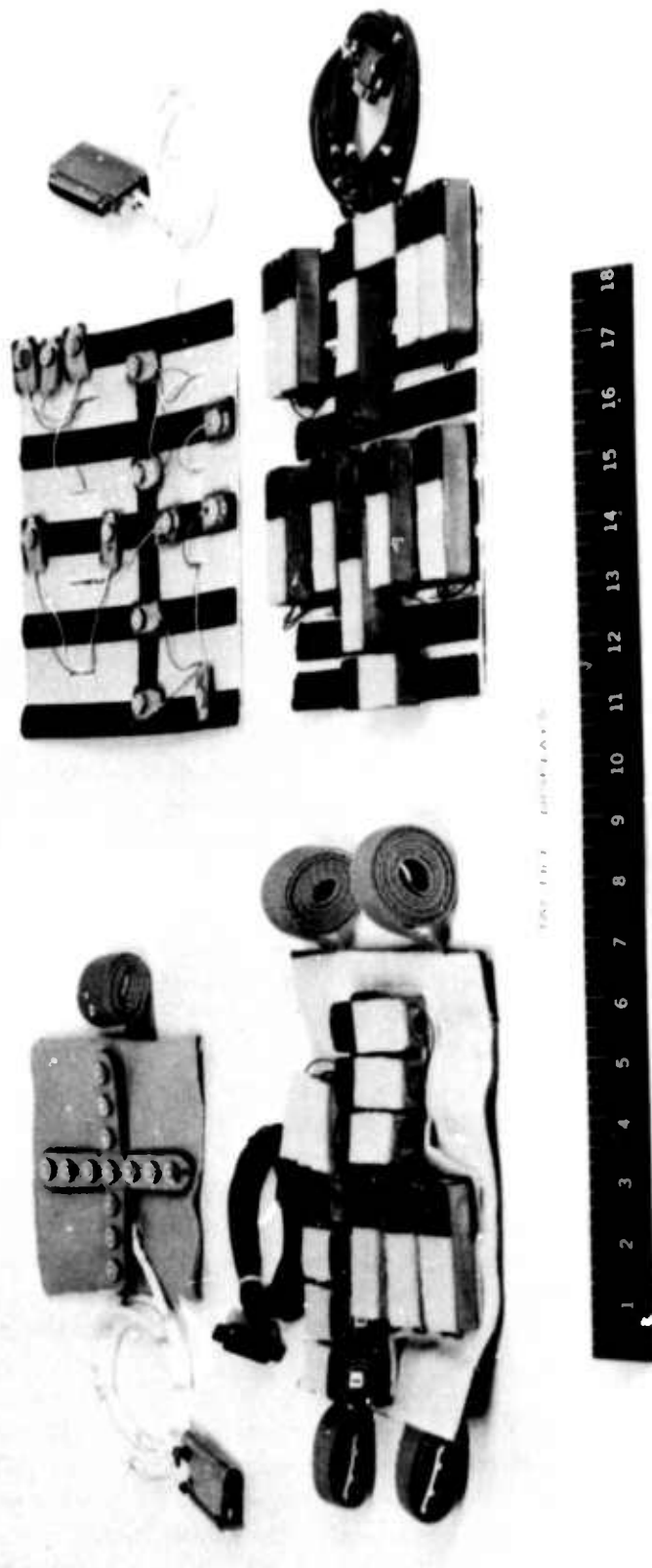


Figure 2-10 Multiaxis Tactile Displays.

were used in each axis. When only 2 tactors were used the direction was difficult to perceive, especially when the other axis was utilizing 3 or 4 tactors. The center, or reference tactor is always the first tactor excited for either axis display; at the high data-rates, its location was not perceived as being in the same location at all times, but displaced away from its actual position in the direction of the ripple motion. This phenomenon appeared to lose its affect at lower ripple frequencies. The sensation intensity level appears directly proportional to the tactor ripple-rate. When the level was set for comfort at the minimum rate, the sensation at the maximum rate was very intense, but it did not have the sting of a high current single tactor stimulation.

From these observations the control logic unit was modified. The number of pulses for each tactor excitation was made selectable (1, 2, 4, 8 or 16). The PRF of the pulses was lowered to 250 hertz to strive for a more generally acceptable stimulation signal. The tactor ripple rate was decreased to the 2.6 to 26 hertz range. The inter-axis interval (IAI) was increased to the range of 125 to 470 milliseconds. The IAI appears to play a very important role in the multi-axis data perception. The IAI was further modified at a later time to allow longer periods when only one axis of data is being displayed.

2.2.3 BANK ANGLE DISPLAY

A circular display was conceived as being a good candidate as a bank indicator. The idea came too late to incorporate its driving function into the developed tactile display system control logic, but the idea was worthy of preliminary exploration.

A small amount of additional circuitry was added to the already existent 3-tactor sequence drivers to allow control of the number of times a display is repeated, the interval between the repeated displays and a sequence initiation switch. A block diagram of equipment is shown in Figure 2-11. The display, as shown in Figure 2-12, consisted of 21 movable electrotactors on a 9x9 inch fabric mounting surface. 20 tactors were symmetrically arranged in a circle every 18 degrees. The circle diameter was bounded by 4 and 8 inches. The last tactor was mounted at the circle's center. Through the use of a wafer switch and a toggle switch any of the 10, 3-tactor vectors can be sequenced in either direction. The controls and logic were part of the multi-display control unit shown in Figure 2-13. This unit also had the capability of driving the three-tactor bimorph array and a polarized electrotactor H display which could be formed by rearranging the tactors used for the circle bank angle display.

During the first tests the data were sufficiently clear with only a single sequence; therefore, data were not taken with repeated sequences. The data were taken on an absolute basis, i.e., there was no vertical or horizontal reference provided during the course of the experiment. The results of the three-subject psychophysical tests presented in Section 4 indicate it is a good candidate for future display work.

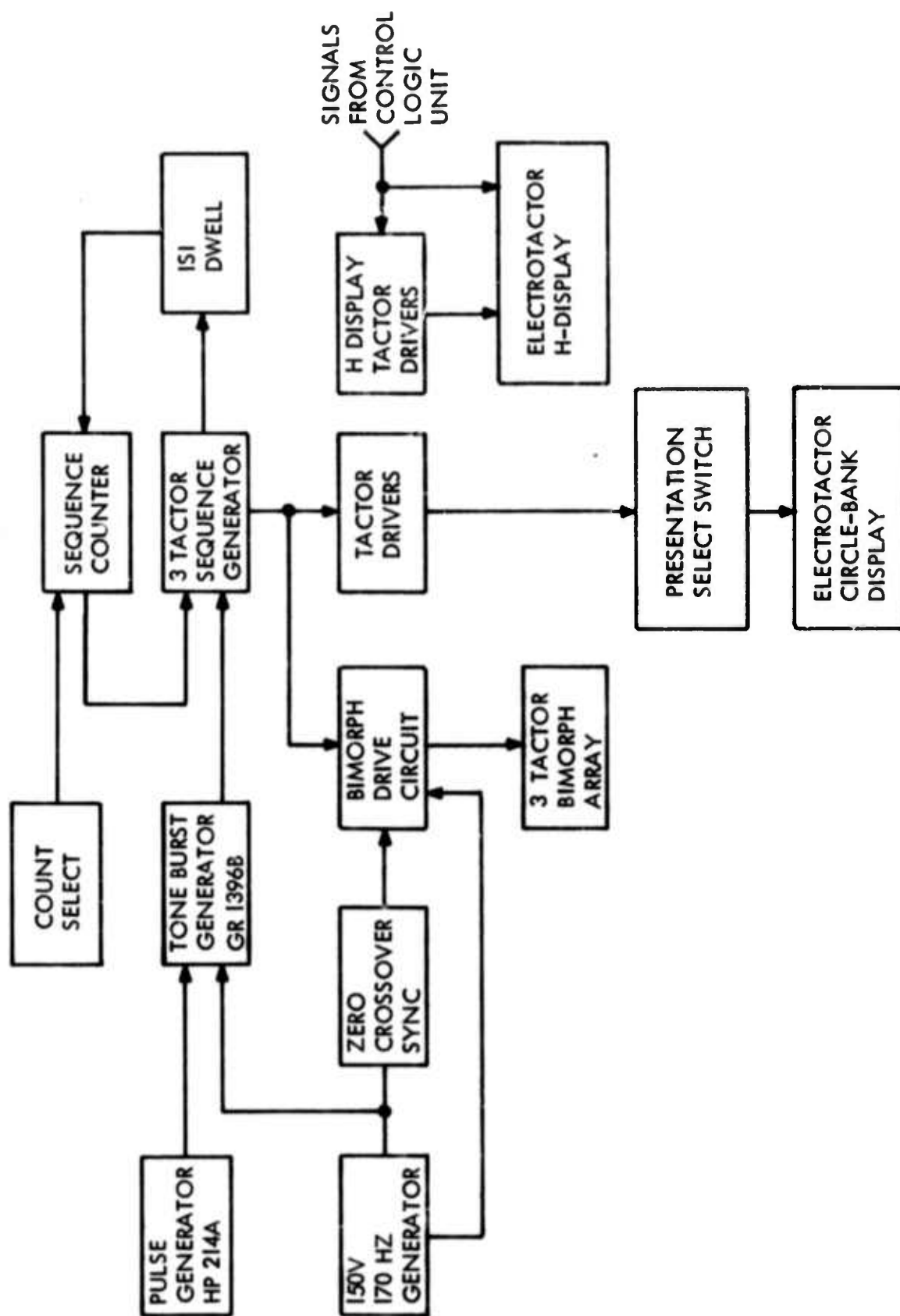


Figure 2-11 Multidisplay Control Unit Block Diagram.

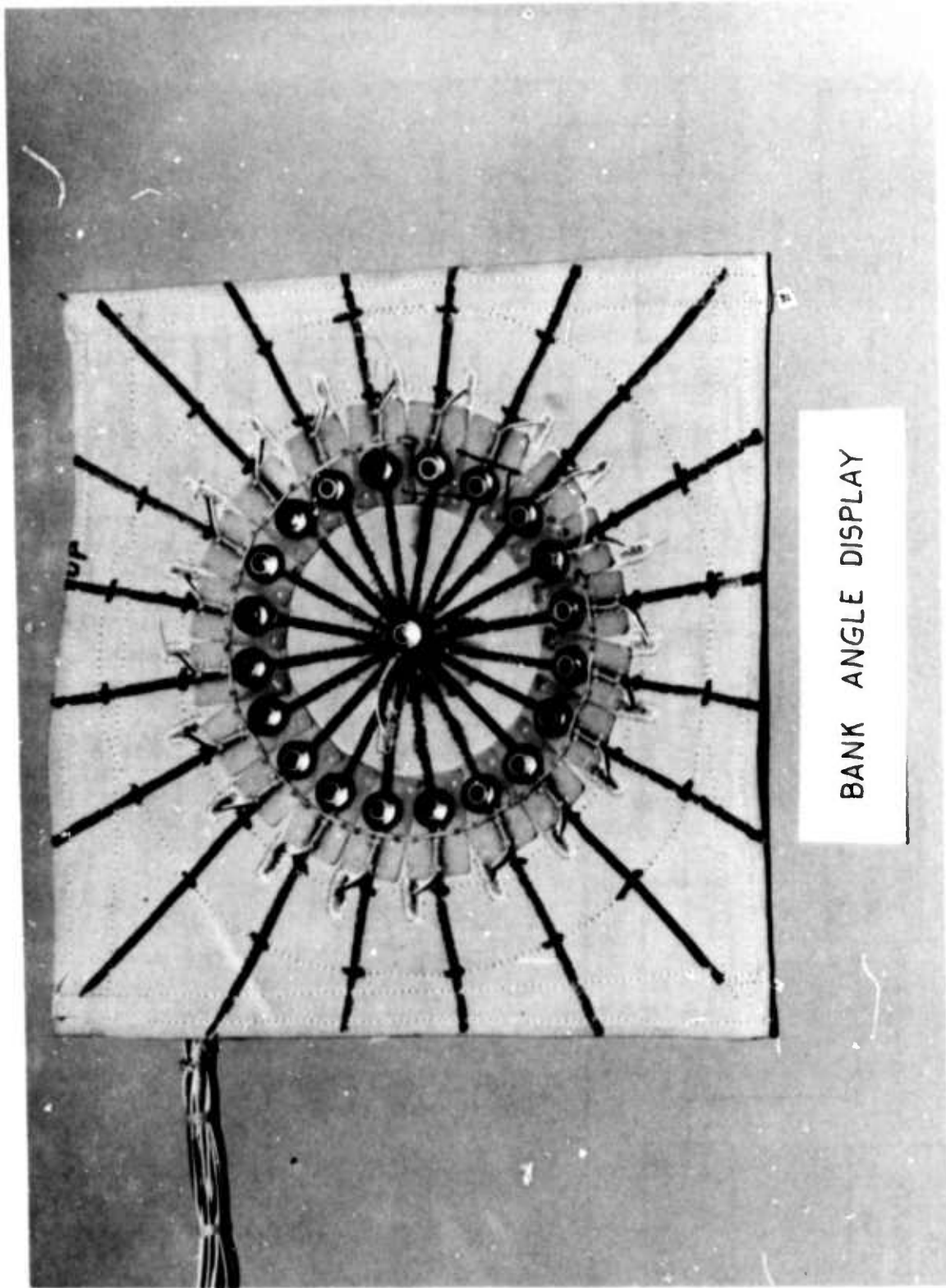


Figure 2-12 Electrotactor Circle Bank Angle Display.

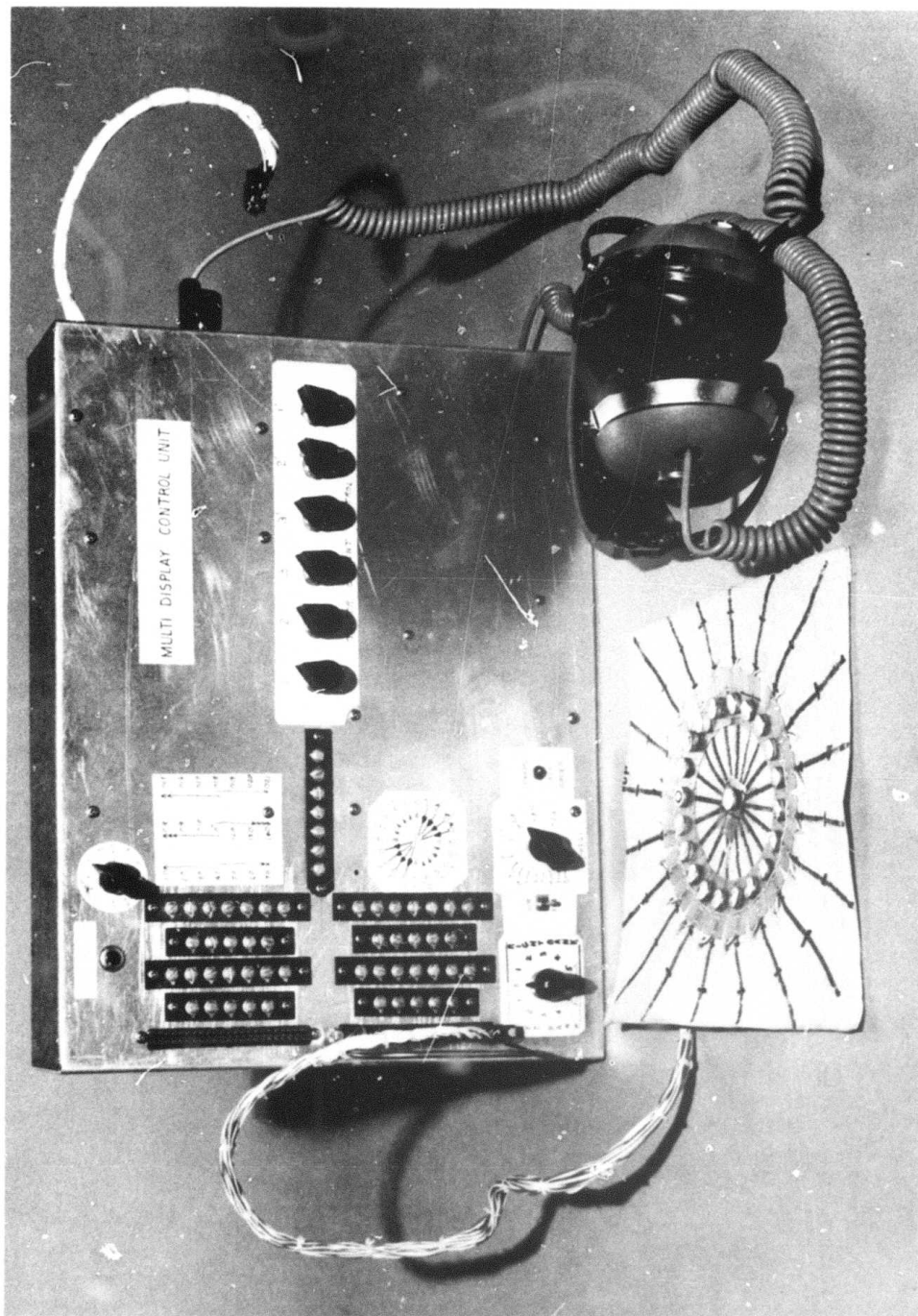


Figure 2-13 Multidisplay Control Unit.

SECTION 3

HARDWARE DESCRIPTION

As discussed in the preceding section the electrotactor and bimorph transducers, have been selected and integrated with the rippled X-Y and H display configurations. This section provides an operational description of the hardware that has been prepared for formal evaluation.

The complete 2-axis tactile display system is shown in Figure 3-1. This equipment has been designed to be portable and to contain all necessary drive circuits. The electronics consists of two units, the control logic unit (CLU) at the right of the picture, and the tactile display unit (TDU) at the left. The TDU receives all of its control functions and some of its output signals from the CLU. All of the displays receive their signals from the connectors on the front panel of the TDU. The four basic displays constructed are shown in Figure 3-2 through 3-5. They are:

- Figure 3-2 Polarized X-Y Electrotactile Display
- 3-3 Polarized X-Y Vibrotactile Display
- 3-4 Nonpolarized X-Y Vibrotactile Display
- 3-5 Nonpolarized X-Y Electrotactile Display

As previously noted, the displays of Figures 3-2 and 3-3 have fixed geometry whereas those shown in Figures 3-4 and 3-5 provide a variable geometry capability. The tactors in the upper and lower right corners of Figure 3-4, and tactors 5, 10, 11, 12 and 13 of Figure 3-5 are not used in these configurations. Figures 3-6 and 3-7 show the tactors repositioned to form the non-polarized H display configurations. Tactor 10 of Figure 3-7 is not used.

3.1 SIMPLIFIED BLOCK DIAGRAM

A simplified block diagram of the tactile display system is illustrated in Figure 3-8. The displays can be operated either manually or automatically. In the manual mode the polarity and number of tactors (+NT) can be independently selected for each axis, the tactor ripple rate (\dot{T}) for each axis can also be independently controlled between 2.6 and 26 hertz. The NT switches can also be

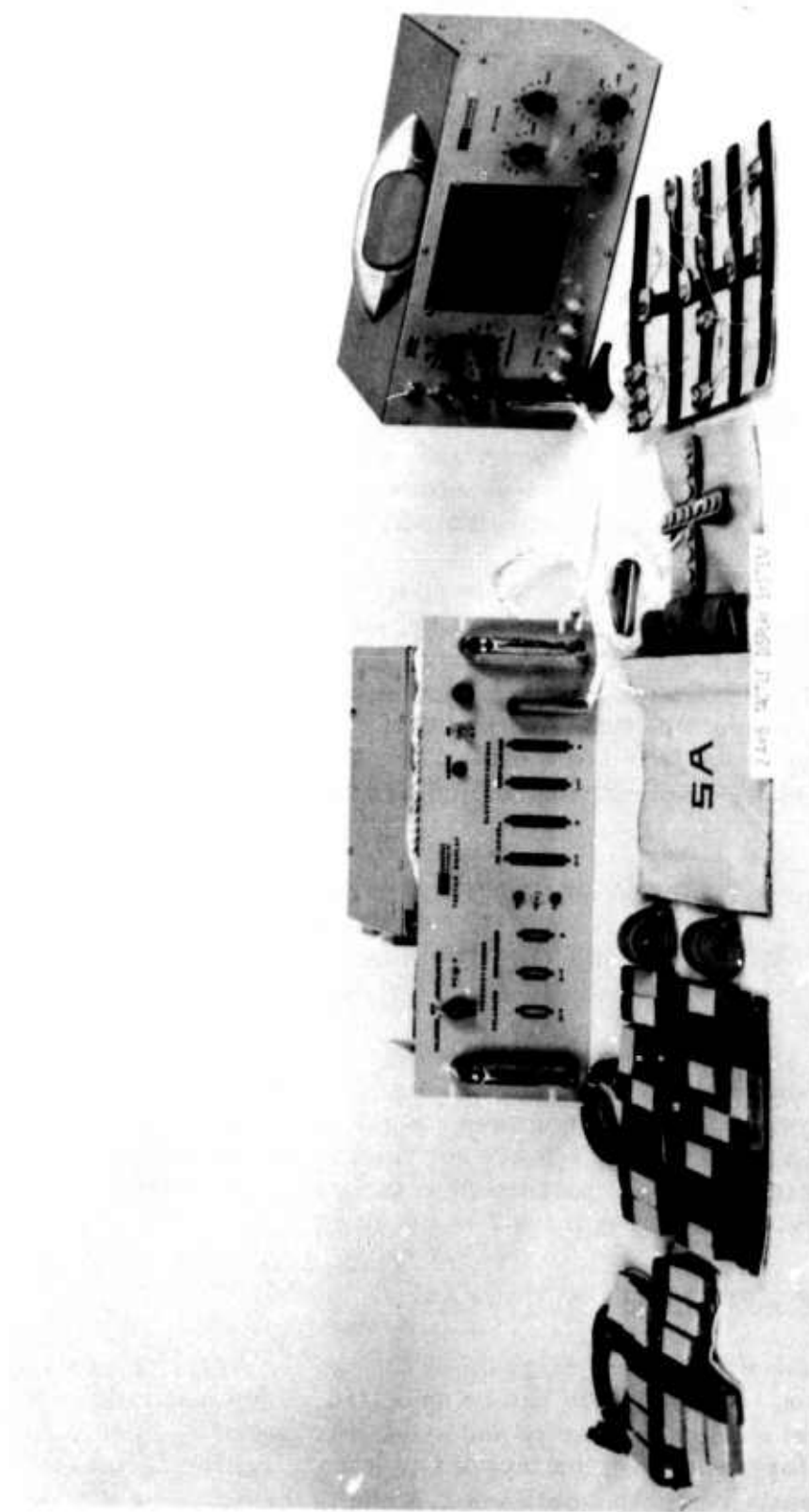
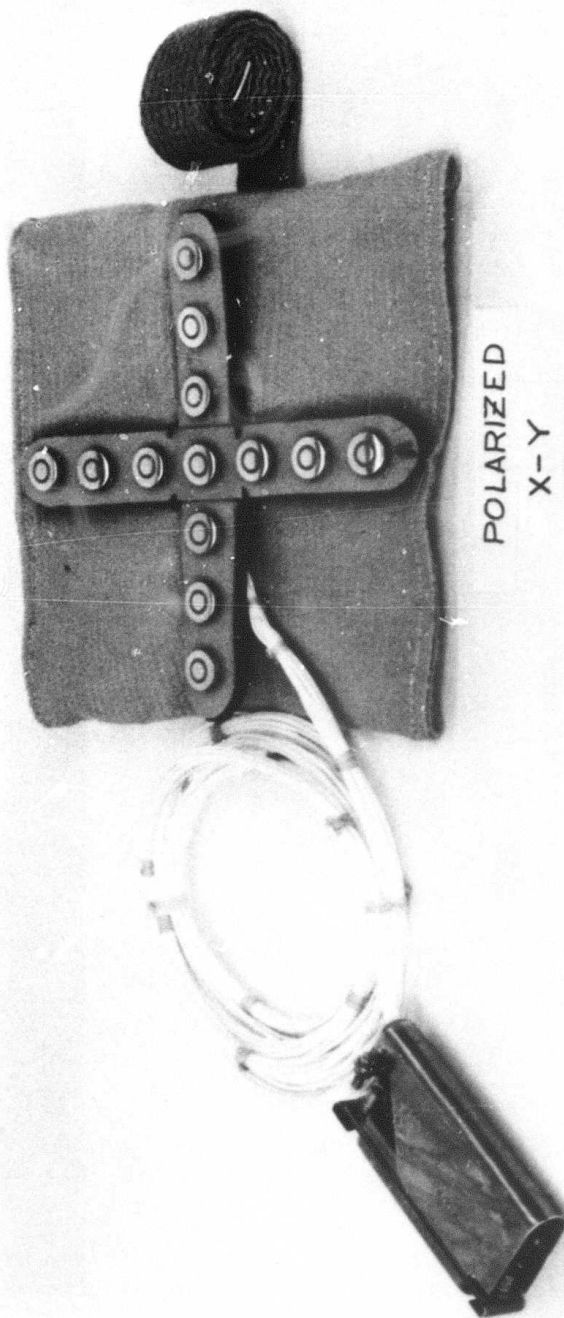


Figure 3-1 Two-Axis Tactile Control System.



POLARIZED
X-Y
ELECTROTACTILE
DISPLAY

Figure 3-2 Polarized X-Y Electrotactile Display.

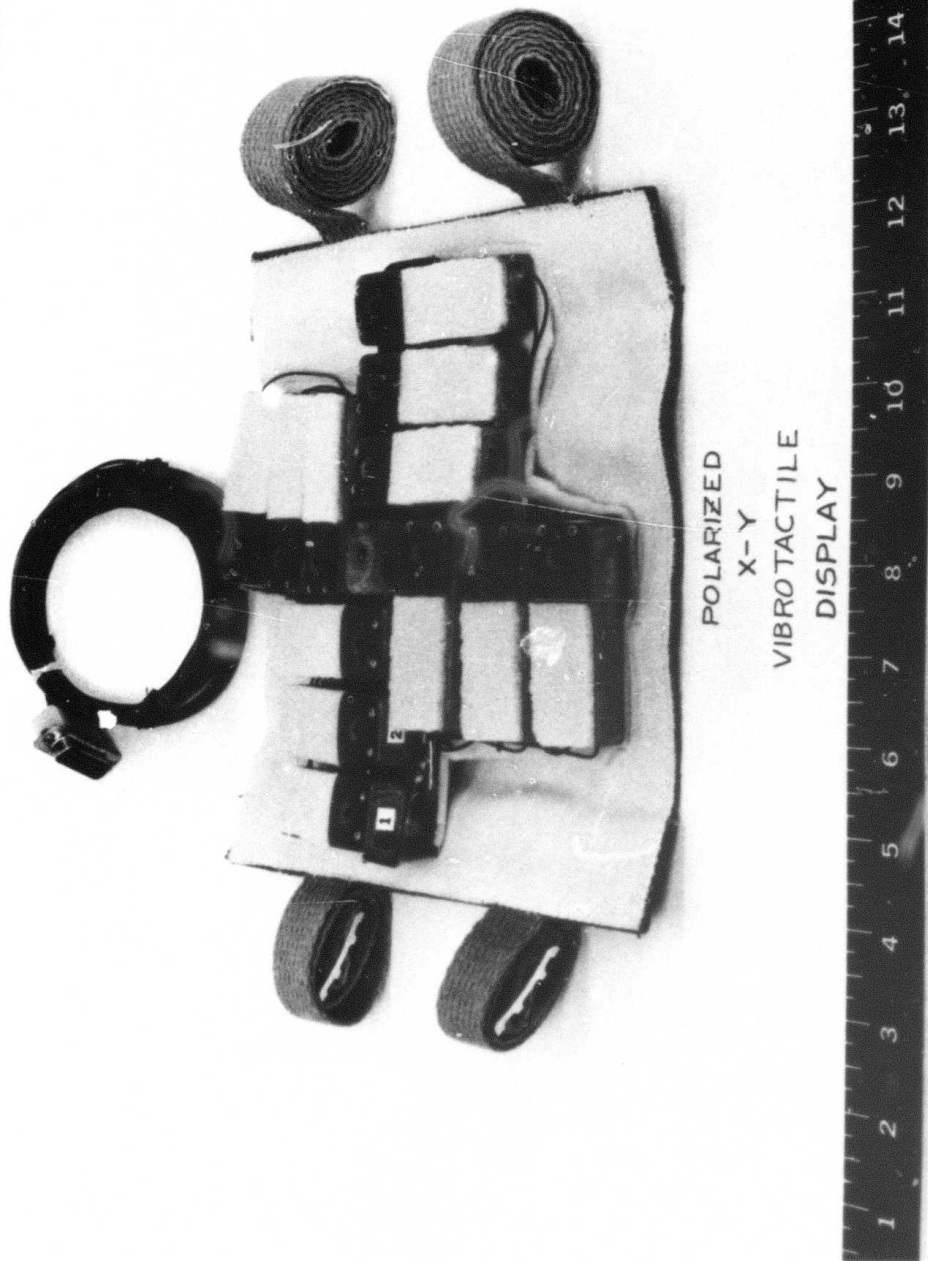
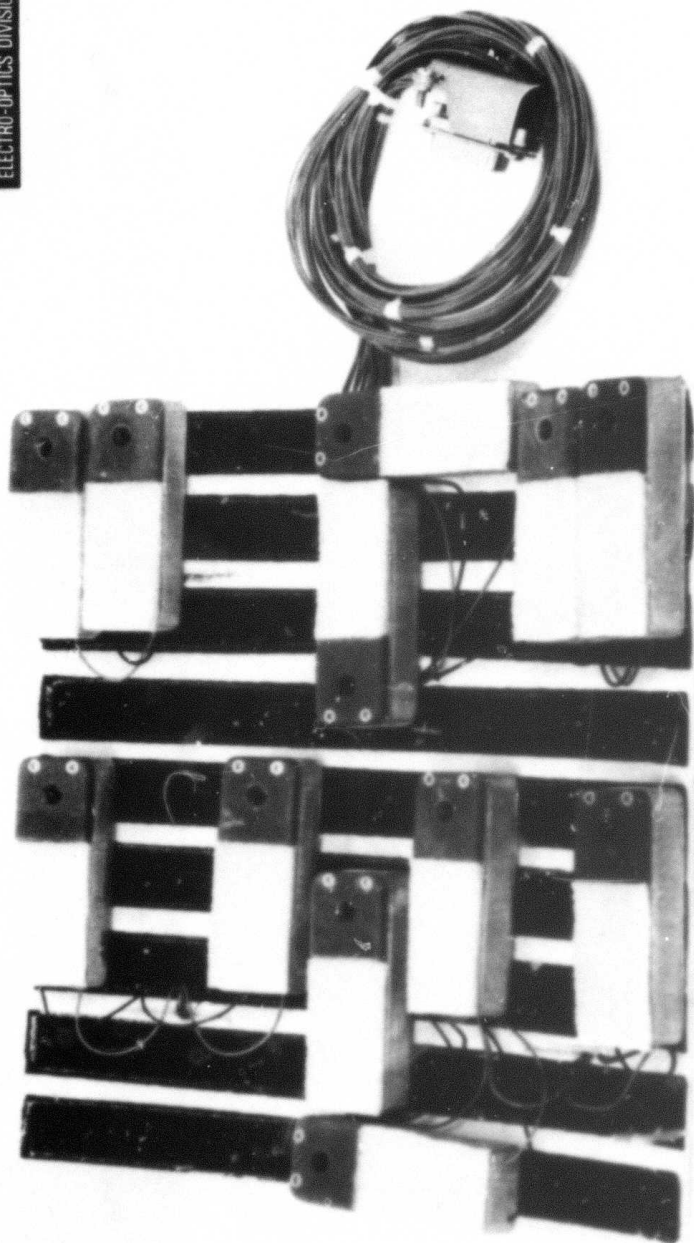


Figure 3-3 Polarized X-Y Vibrotactile Display.



NONPOLARIZED
X-Y
VIBROTACTILE

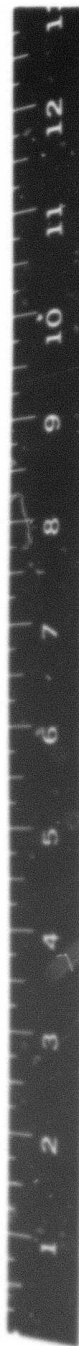


Figure 3-4 Nonpolarized X-Y Vibrotactile Display.

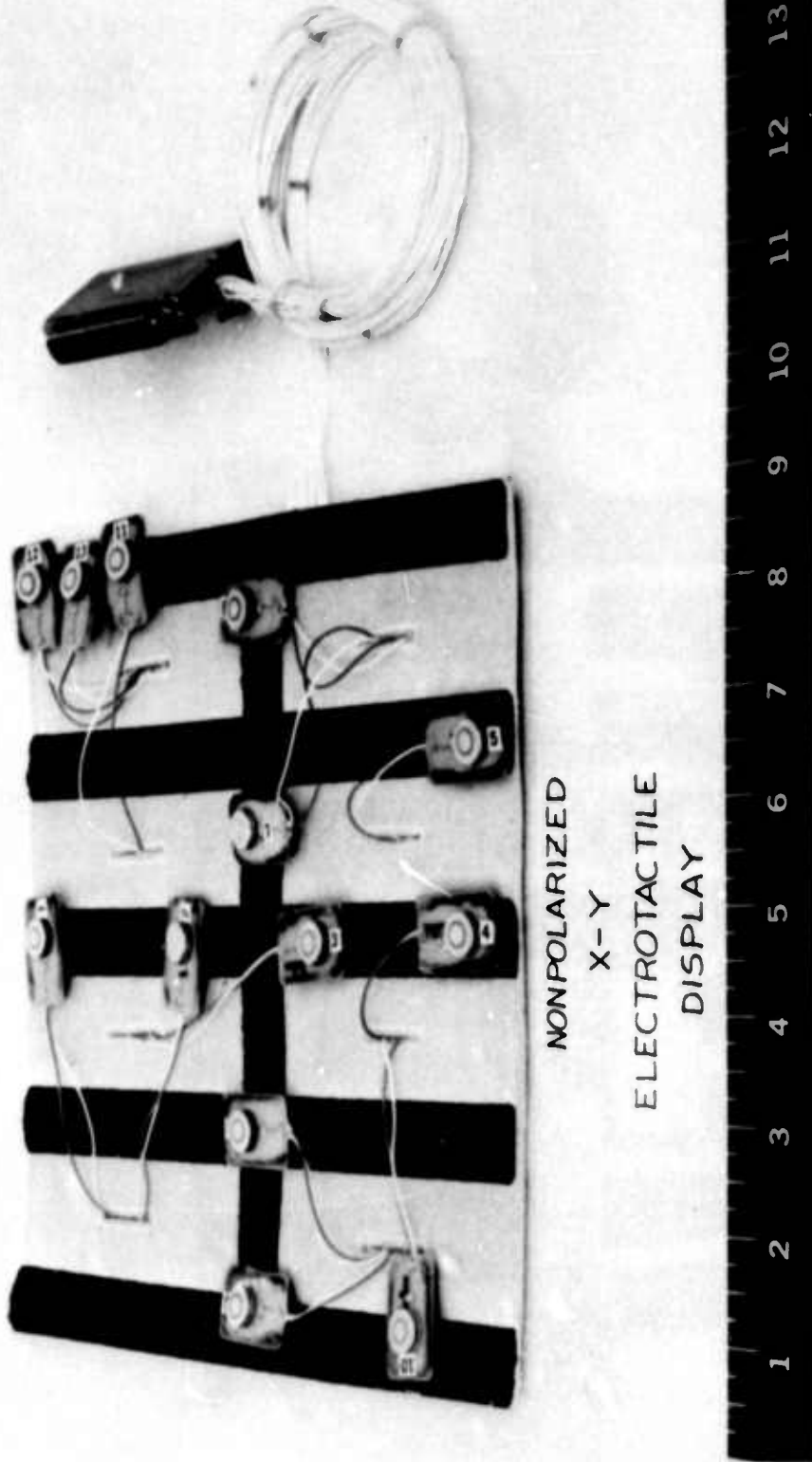
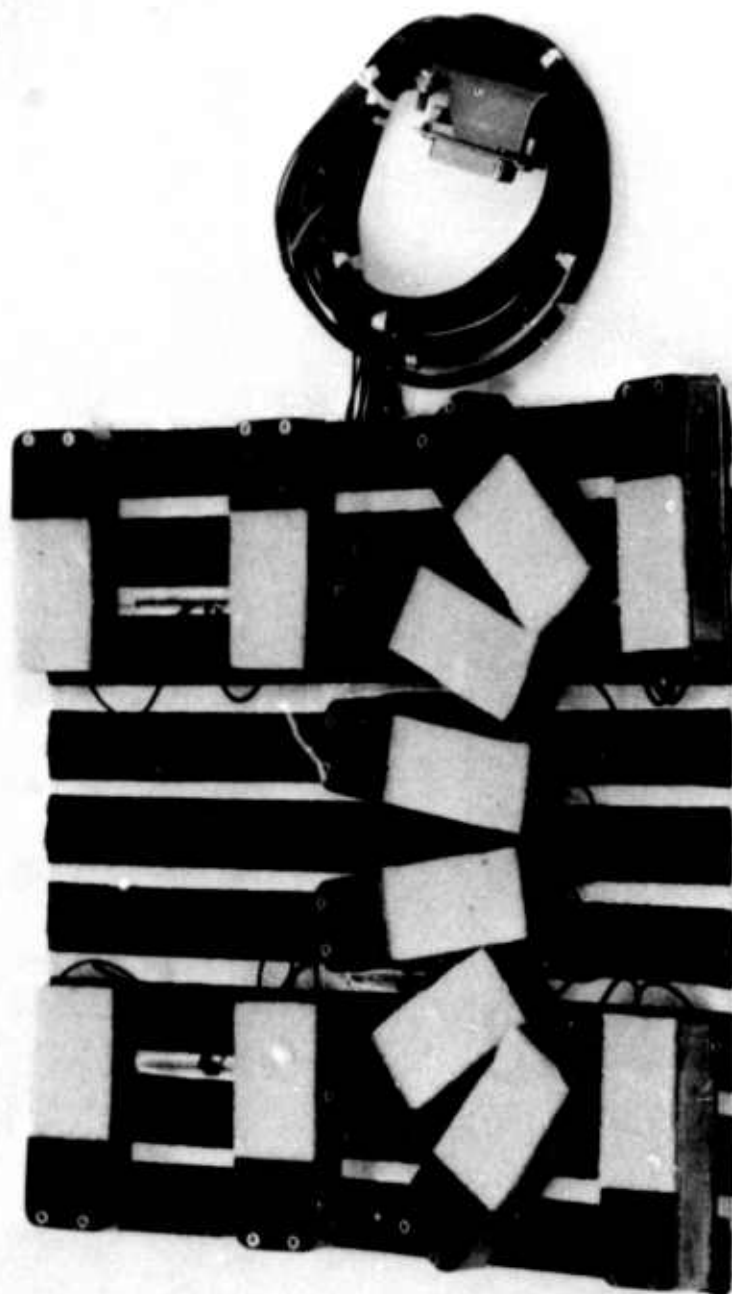


Figure 3-5 Nonpolarized X-Y Electro-tactile Display.



NONPOLARIZED
H
VIBROTACTILE
DISPLAY



Figure 3-6 Nonpolarized H Vibrotactile Display.

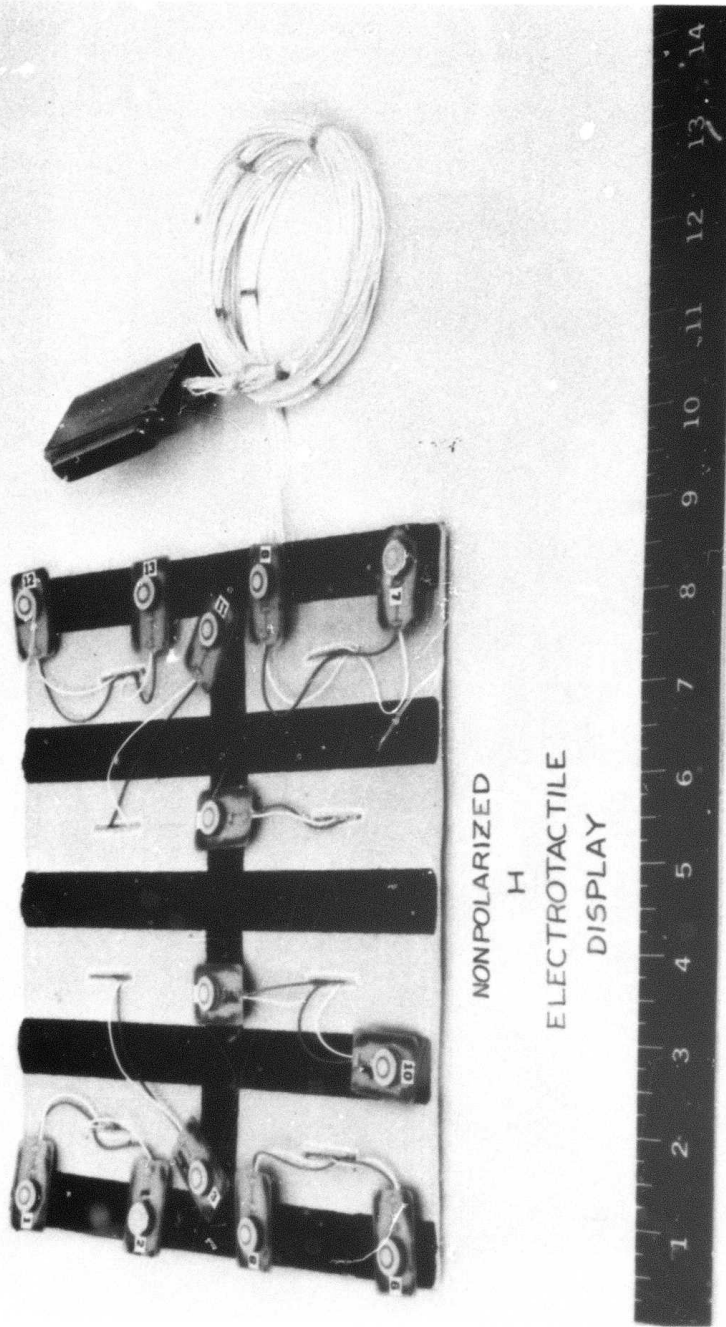


Figure 3-7 Nonpolarized H Electro-tactile Display.

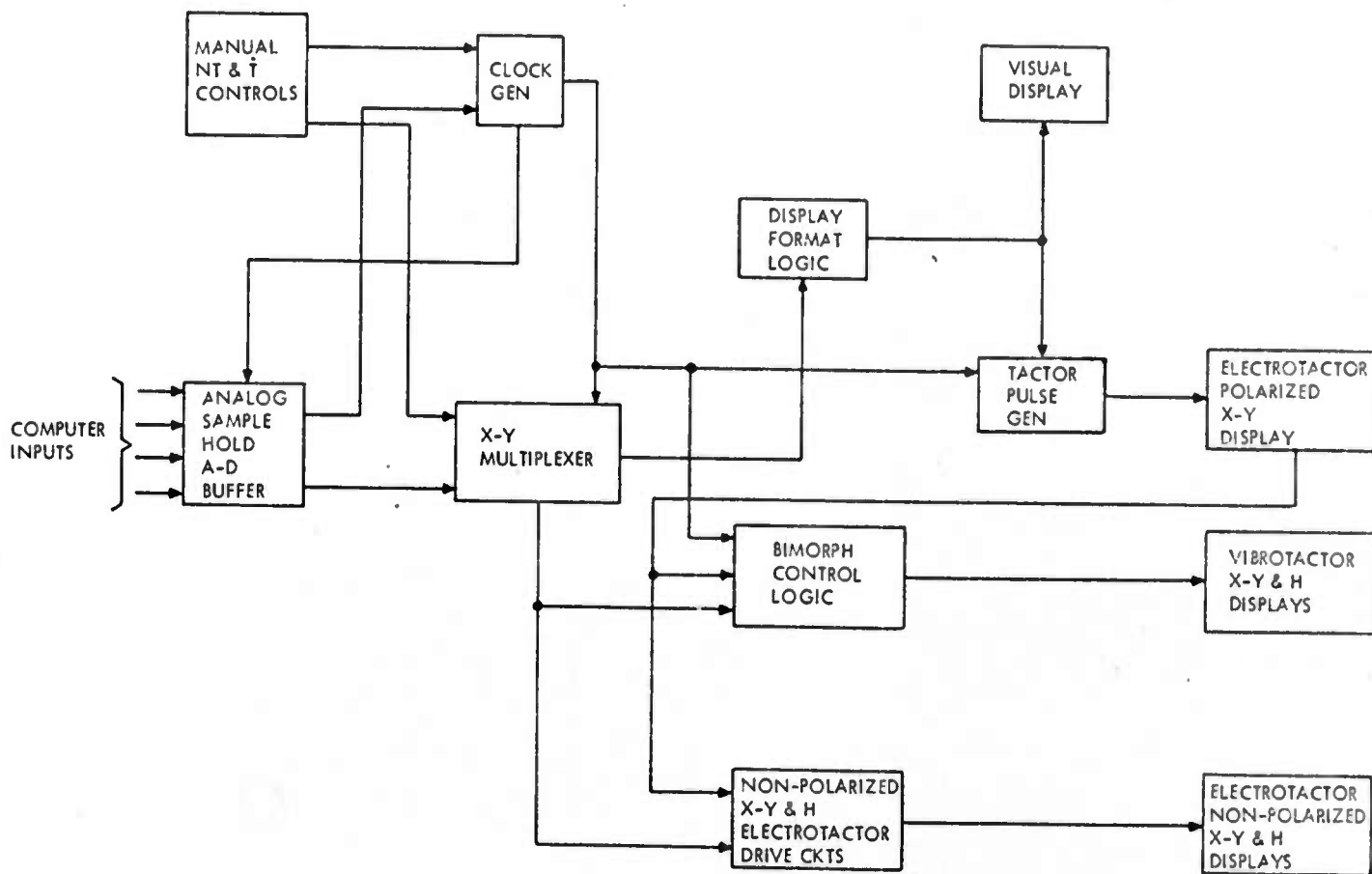


Figure 3-8 Tactile Display Simplified Block Diagram.

be used to select single axis operation. The T generators control the system clock and when there are data to be displayed in their respective channel, a clock pulse is generated for each tactor period. The clock pulse enables sampling of the NT and T analog input data when in the automatic mode.

The NT input signal is parallel converted to 6-level digital data and routed to the X-Y multiplexer. The multiplexer generates the display sequence, alternating between axes. Immediately following the last tactor period in one axis, the inter-axis-interval (IAI) or dwell period is initiated. The IAI period is manually controllable between the limits of 125 and 350 milliseconds. When data are being presented on one axis it has been desirable to have longer dwell times, consequently, a DWELL MULTIPLIER control is available to provide the increased IAI's. The logic automatically switches in the multiplier during 2-axis tracking problems when one axis of the data has been nulled.

When no data on either axis are being presented, the clock signal derives its timing from the reference oscillator. The reference clock period excites the center tactor of the polarized X-Y displays once every 7 seconds.

The output of the multiplexer is a 2, 3, or 4 tactor period sequence for the axis presently being processed. These data, along with its detected polarity, axis identification, and format control are sorted out by the Display Format Logic to excite the proper tactors in the desired sequence. The output provides the sequences for either the POLARIZED or NONPOLARIZED X-Y displays, and directly controls the LED visual display on the front panel of the Control Logic Unit.

The electrotactor pulse generator provides stimulating-current-pulses synchronized with the tactor period gates of the multiplexer. Eight (8), 50 micro-second pulses, at a rate of 250 hertz are generated during each tactor period. These pulses are routed to the proper tactor driver by the tactor period gates from the multiplexer. For each pulse, the tactor driver delivers a constant current pulse to the tactor load. The current level is controlled by the INTENSITY control on the CLU front panel.

The nonpolarized X-Y and H electrotactor drive circuits generate signals to excite the initial tactor for each axis sequence. The center tactor is always the first excited in the polarized display. In the nonpolarized display it is the one on either end depending on the polarity of the error signal. The required simultaneous drive signals are also generated for the H display.

The bimorph control logic receives the tactor period gates, clock and axis selection data. With these data and the selfcontained bimorph power supply (170 Hz, 150 VRMS), the bimorph vibrotactors are excited with a 6 cycle burst of the 170 Hz drive signal. The triac controlling the tactor on-period is switched at the zero crossover times of the 170 Hz signal to minimize any possible RFI problems.

3.2 FUNCTIONAL BLOCK DIAGRAM

The content of this section will be held mostly to a functional block level as most of the system consists of logic and switches. In the case of the tactor drivers, the elemental level will be incorporated for a better understanding of the operation. The functional block diagram illustrated in Figure 3-9 will be used as the basis of the description.

The displays can be controlled by two methods; first by manually controlling the position, number, and ripple rate of the tactors; and second, automatically, i. e., the analog input signals NT and \dot{T} for each axis control the position, number, and ripple rate of the tactors.

3.2.1 MANUAL CONTROL

The input signals are controlled by the 2 NT-AUTO and TACTOR RATE controls on the right side of the CLU as shown in Figure 3-10. Each axis has its own set of controls. The NT-AUTO switches have 8 positions with the extreme clockwise position of each being the AUTO mode. The other 7 positions allow manual selection of the number of tactors used in a data sequence and the polarity or position of the tactors in the display. When in the manual mode, the tactor ripple rate (or intertactor interval (ITI)) is controlled by the TACTOR RATE control. The rate controls are calibrated in ITI periods of 22 to 350 milliseconds which correspond to 20 to 2.6 hertz. The NT-AUTO switches are used to provide single axis operation by placing one switch in the zero position. The manual operation is very useful for checking the operation of the system and familiarizing the subject with tactile perception.

3.2.2 AUTOMATIC CONTROL

The analog input signals used to control the displays are connected to the 4 BNC jacks on the lower left part of the CLU front panel. These signals have no control until the NT-AUTO switches are in the AUTO position. There are two inputs for each axis, a NT and \dot{T} . The signal to the NT input controls the polarity and the number of the tactors used in the display sequence. The selected quantized input levels are 1, 4 and 9 volts. The computer scaling can be controlled to furnish various error designations for these levels. A negative 5-volt signal to the X-axis NT input will select the center and the first two tactors along the negative X-axis of the polarized display; for the nonpolarized display, the first 3 tactors from the right would be selected and they would be rippled from right to left. The signal to the \dot{T} input controls the tactor period, or ripple rate. Figure 3-11 shows the relationship of the voltage level to ripple frequency (0 to 10 volts varies the ripple frequency from 2.6 to 26 hertz). The voltage to frequency conversion accuracy between the plus and minus input and the two axes (4 combinations) is ± 6 percent.

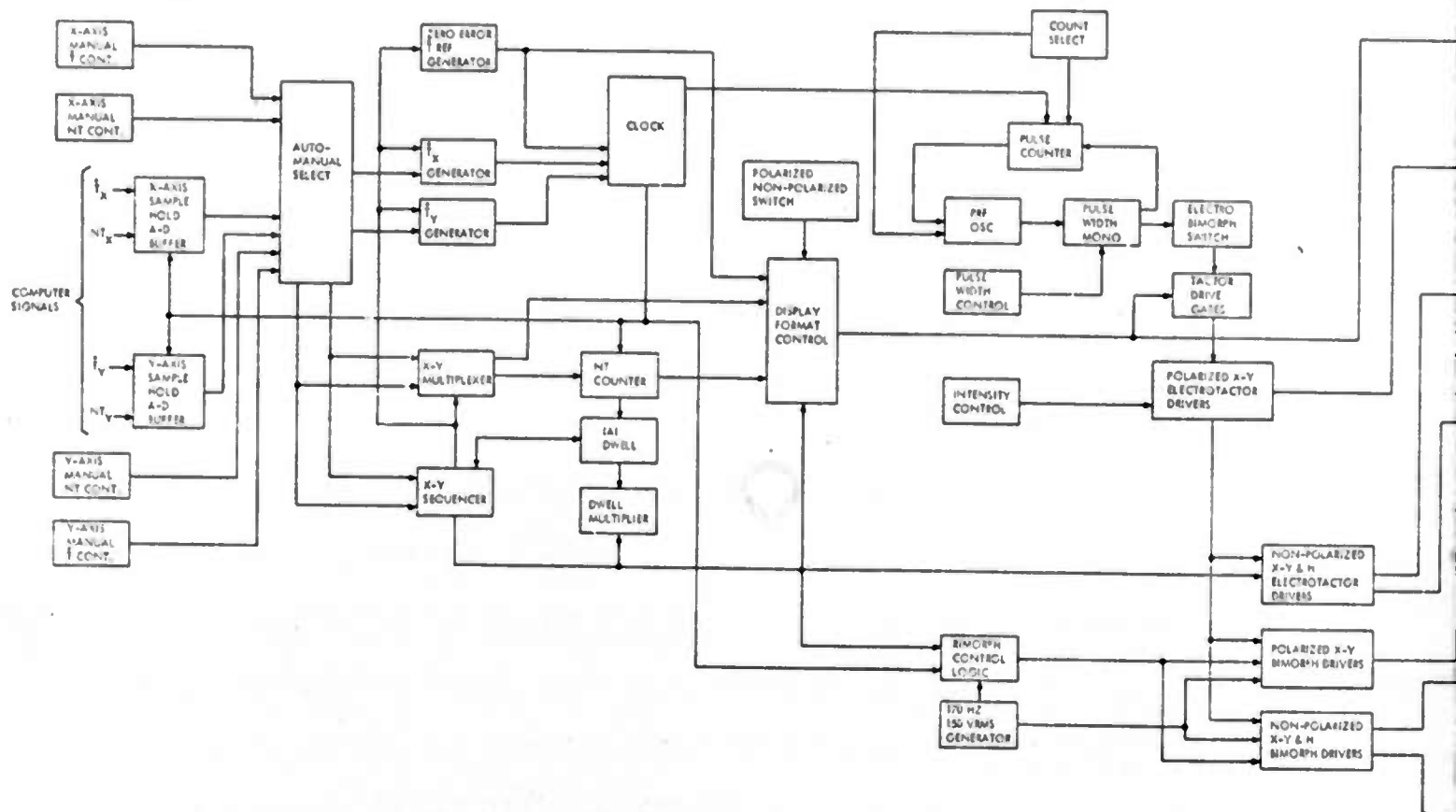


Figure 3-9

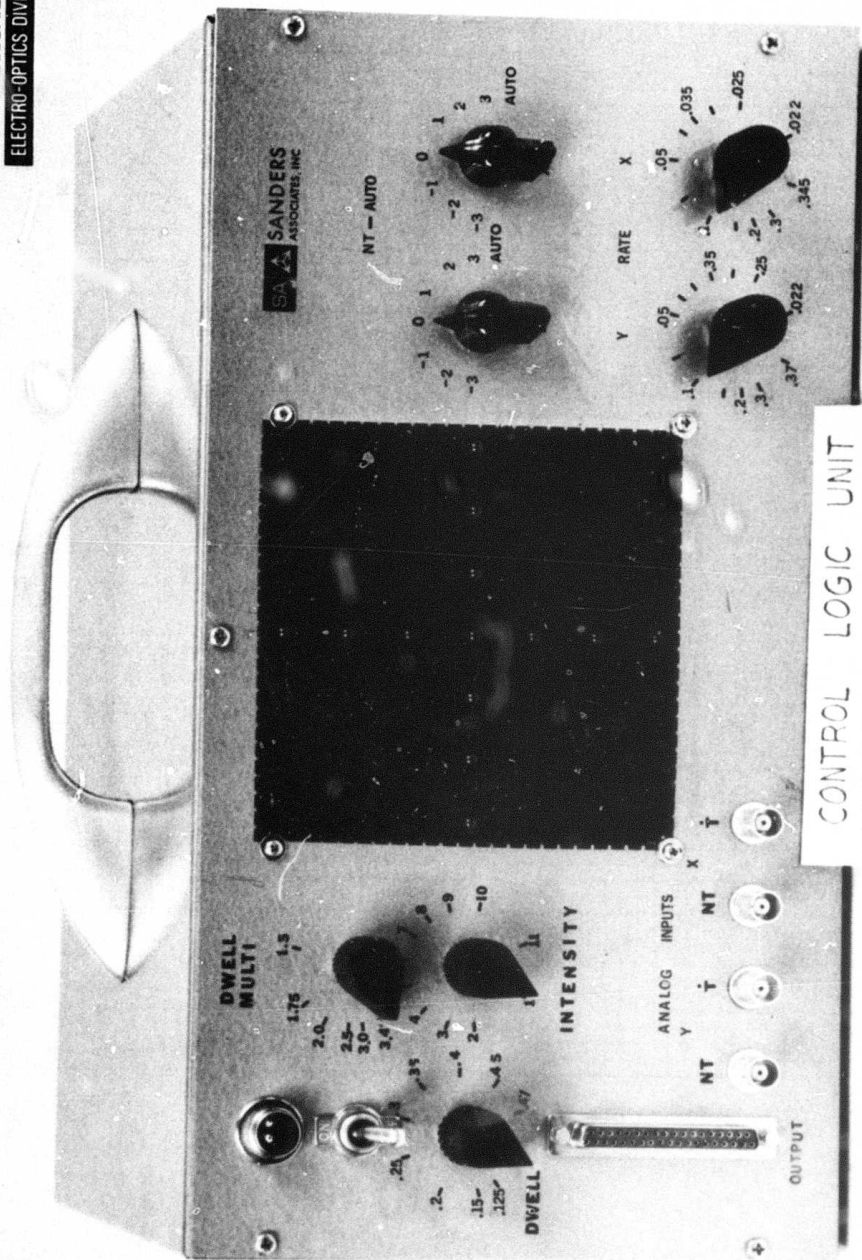


Figure 3-10 Control Logic Unit - Front View.

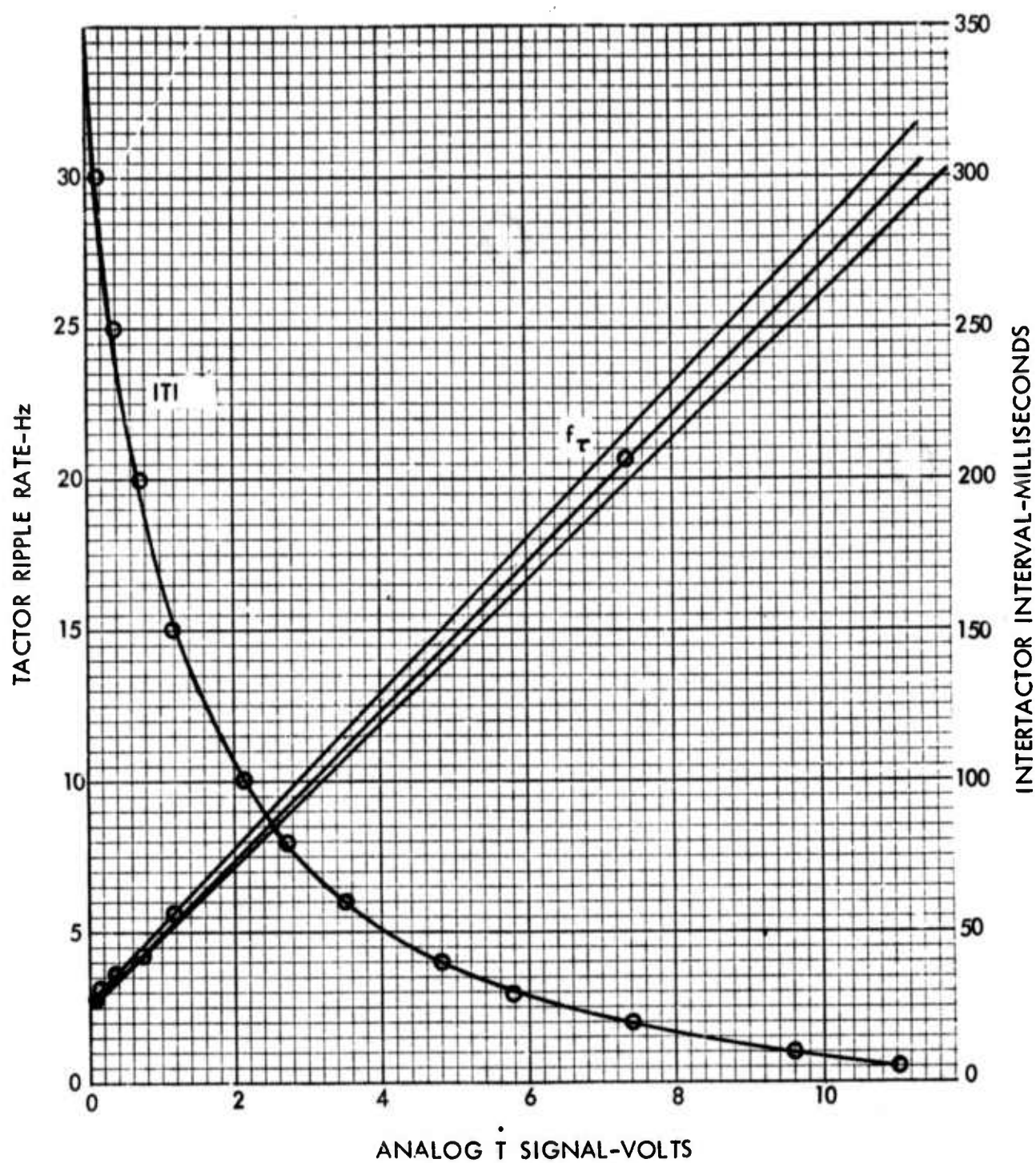


Figure 3-11 Ripple Rate vs. \dot{T} Signal.

The input signals are sampled and held for processing during the dwell period. The outputs of the \bar{T} sample and hold circuits are processed to obtain the absolute value which is then used to control a transconductance amplifier. The current signal from the transconductance amplifier is used to control the capacitor charge time of a unijunction oscillator used to generate the tactor ripple rate frequency. The signals from the NT sample and hold circuits are routed directly to parallel A-D converters incorporating plus and minus voltage comparators and logic elements to obtain the 7 levels of quantized digital data (+1, 2, & 3 and 0). These digital signals are directly OR'ed with their respective NT-AUTO switch positions from which the sequencer and multiplexer obtain their input signals.

3.2.3 CLOCK

The display period is contingent on the tactor ripple rates of the 2 axis data and since these are independent variables, the clock has been designed to be controlled by the data axis being displayed. The clock period is equal to the displayed data tactor period, consequently its rate changes for each axis. The X and Y \bar{T} oscillators operate between 83 and 830 hertz and the selected oscillator drives a divide-by-32 counter used to generate one clock pulse for every 32 oscillator cycles. One oscillator period prior to the clock output is detected to produce a preclock signal used to monitor the NT counter and NT input data convergence.

When there are neither X or Y data, the clock is controlled by the reference oscillator. During this period, the clock causes the reference, or center tactor of the polarized X-Y display to be excited once every 7 seconds. The instant data appear at either input, the reference period is terminated and the received data are processed and displayed.

3.2.4 MULTIPLEXER

In order to provide a more coherent explanation of the operation of this part of the system, the NT counter, IAI dwell and the sequencer will also be discussed for they form an axis word loop. As a starting point, assume the last tactor in an X-axis word has just been excited. The output of the NT counter is compared to the output of the multiplexer during each preclock pulse period. For our example then, the next preclock pulse will find the NT counter has counted the required number of tactor periods, thus, it will trigger the IAI dwell mono (125 to 470 milliseconds) signifying the X-axis word has been completed. As mentioned before, the dwell period is used to update the sampled analog input signals, in this case the sampled Y axis data will be used next. The dwell signal also resets the NT counter. The termination of the dwell period generates a sampling pulse used to toggle the X-Y sequence flip-flop. The flip-flop will alternate the axis selection unless, or until, there is zero information on one axis. In this case, the flip flop will be held in the state necessary to continuously repeat the display of the axis having data. This is done by controlling the direct preset and clear inputs of the flip flop by gates monitoring the existence of signals on both axes. The

output of the axis sequencer is used by the display format control to switch the tactor gates generated by the NT counter to the desired axis. The sequencer output is also routed to the multiplexer where it determines which data from the NT-AUTO switches are used for comparison with the NT counter output, in the present example case the Y-axis is selected.

The polarity of the data present at the NT-AUTO switches is detected and is also an input to the multiplexer. The polarity signal from the multiplexer is routed to the display format where it is used to route the tactor gates to the desired tactors.

At the completion of the dwell period, the clock pulses begin toggling the NT counter. The counter generates 2, 3, or 4 gates wherein the rise time of one is coincident with the fall-time of the previous gate. The length of the gate is directly related to the tactor ripple frequency since it is controlled by the clock. Prior to each clock pulse, the count of the NT counter is compared with the NT values from the multiplexer. When they coincide, dwell is initiated and the cycle repeats.

The absence of data on one axis is sensed and activates the DWELL MULTIPLIER (1.25 to 3.4 times the DWELL setting) to automatically lengthen the dwell period for single axis data presentation.

The tactor gate sequence generated by the NT counter is used to control the excitation of the desired tactors. The tactor gates are routed to the display format control where they are combined with the polarity and axis selection signals to select the required tactors in the desired temporal order.

3.2.5 FORMAT CONTROL

The display format control accepts the tactor gates from the NT counter, the polarity signal from the multiplexer and the axis signal from the sequencer to select the correct tactor excitation sequence for either the polarized or nonpolarized X-Y display. The DISPLAY switch (NON POL or POL) on the rear panel of the CLU determines the type of display (Figure 3-12). The output of the display format directly controls the LED visual display on the front panel of the CLU.

The polarized X-Y display consists of a center reference tactor and then 3 tactors along each direction of the two axes. The operation of the center tactor is not controlled by either the polarity signal or the axis signal, it always receives the first tactor gate from the NT counter. The axis signal activates the final gates to the 6 tactors of the axis for which data are being processed. The polarity signal determines which 3 of the 6 tactors are to be used, thus for a positive NT_y signal the upper 3 tactors of the Y-axis would be selected. The 3 selected tactors are then sequenced by the tactor gates in a linear progression from the reference tactor which is always the first tactor excited for both axes of the X-Y polarized display.

With the display switch in the NON POL position, the display format controls the nonpolarized X-Y display consisting of only 4 tactors on each axis. For this display, the polarity signal determines the tactor sequence direction since the same 4 tactors are used to display both polarities of the NT signal. As before, the axis signal controls the final gates to the 3 tactors of the plus X and Y axis. The negative X and Y axis gates are locked out during nonpolarized operation because they are not needed. The central reference tactor is also not required because the nonpolarized display has no center, or common tactor shared by both axes. For the polarized X-Y display, the first tactor gate from the NT counter always controlled the reference tactor. The nonpolarized display requires that the first tactor gate control any of the 4 outside position tactors. For instance, a positive NT signal will strobe the X-axis from left to right; negative - right to left, the Y-axis is strobed upward for a positive signal and down for a negative. The visual display for the nonpolarized format uses the first quadrant LED's wherein the center light is shared by both axes. This was only done for the visual display because it eliminated design and fabrication time which would have been necessary to provide a direct visual analogy of the tactual display. Other than the shared light and axis translation, the visual display presents the data in the proper sequence. There is a switch on the rear panel of the CLU which controls the power to the LED's. With the switch in the OFF position, the subject is denied visual orientation of the displayed data.

3.2.6 TACTILE PULSE GENERATOR

The tactile pulse generator provides 1, 2, 4, 8 or 16 pulses of controllable width for each tactor period. These groups of pulses are then gated by the display format control to drive the tactor constant-current-drivers. Prior to receiving a clock pulse, the PRF unijunction oscillator is held in an off condition by the pulse counter. The clock pulse resets the pulse counter which in turn, turns on the oscillator. The count select switch position determines which flip flop output controls the operation of the oscillator, hence selecting whether there will be 1, 2, 4, 8 or 16 pulses generated before the oscillator is turned off. For either 1, 2, 4 or 8 pulses, the PRF is 250 Hz and for 16 pulses the PRF is 500 Hz. The output of the PRF oscillator triggers the mono used to control the pulse width of the constant current tactor stimulation signal. The pulse width control is on the back panel of the CLU and although it can vary the pulse width between 10 and 400 microseconds, it is normally set between 40 and 100 microseconds. One output of the mono is used to toggle the pulse counter, the other is routed through the ELECTRO-BIMORPH switch to the tactor drive gates, which guided by the format display signals, route the generated pulse group to the required constant current driver. Once the selected number of pulses has been generated, the PRF oscillator is turned OFF and remains off until the next tactor period is initiated by the occurrence of a clock pulse. The ELECTRO-BIMORPH switch is used to eliminate the pulse group during vibrotactile operation; in this mode the desired

output signal is the full tactor period because the bimorph vibrators require a different excitation signal.

3.2.7 ELECTROTACTOR DRIVERS

The electrotactor drivers receive their signals from the tactor drive gates of the tactor pulse generator. Each tactor has its own constant current driver. The stimulation signal is derived by the constant current discharge of a capacitor through the skin in contact with the tactor during each pulse of the pulse group. The stimulation current is controlled by controlling the voltage level across a 1000 ohm resistor in the emitter circuit of the output transistor, thus, if a 5.7 volt pulse is applied to the base of the transistor, 5 volts will appear across the 1000 ohm resistor to hold the capacitor discharge rate at 5 milliamperes. The INTENSITY control on the front panel of the CLU regulates the peak voltage magnitude of the pulse group appearing at the base of all the output transistors.

3.2.8 BIMORPH CONTROL LOGIC

The function of the bimorph control logic is to switch the bimorphs on for 6 cycles of the 170 hertz power and to synchronize the tactor drive gates with the zero crossover-points of the 170 hertz bimorph voltage. This is necessary to eliminate RFI problems when switching the 150 Vrms power to the bimorphs. The 170 hertz power-supply consists of an oscillator, intermediate amplifier, and a push-pull power amplifier to obtain the necessary 150 volts rms. The input power for this supply is controlled by the switches on the Tactile Display Unit (TDU) (Figure 3-13). The output of the oscillator is used as the input to the zero crossover-detector.

The clock pulse is used to reset the logic prior to each tactor period. The first 170 hertz crossover-point occurring after the clock pulse, sets the gate flip-flop which is then left in this state until 6 cycles are counted. The toggled reset of the gate flip-flop is also coincident with the 170 hertz zero crossover-points. The output of the gate flip-flop is a 36 ms gate (6 cycles of 170 hertz) and is bounded by the tactor period. The output of the gate flip-flop is AND'ed with the individual tactor drive gates to turn on the selected bimorph vibrator. During the period in which the gate flip flop is off, a dummy load is turned on allowing a constant load on the bimorph power supply.

The bimorph drive circuit converts the logic level signal to the voltage and current level necessary to control the triac switch. The triac is in series with the bimorph. The triac gate is constantly driven during the entire 6 cycle gate period to minimize the transient effects of the individual crossover points occurring during the 6 cycles.

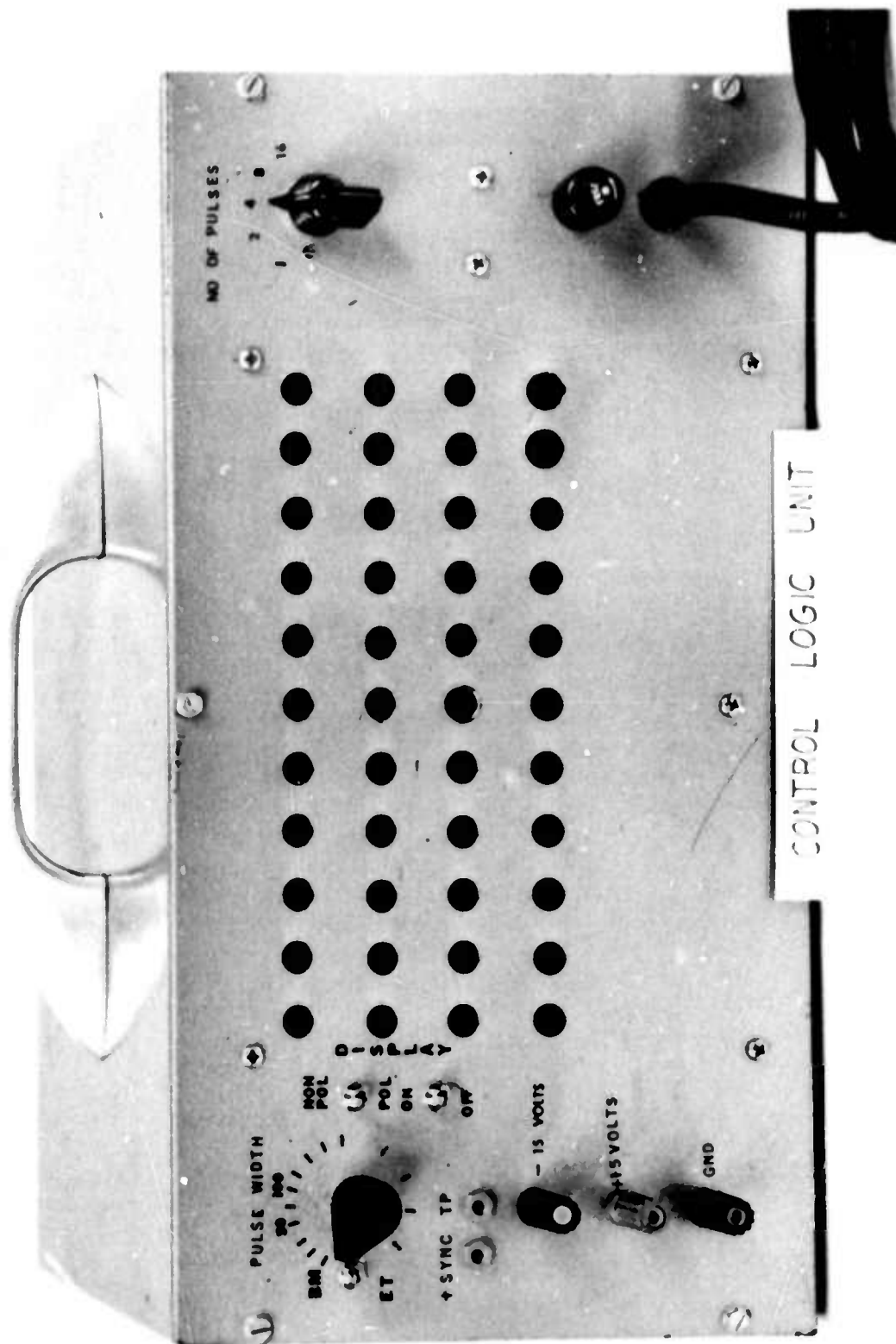


Figure 3-12 Control Logic Unit - Rear View.

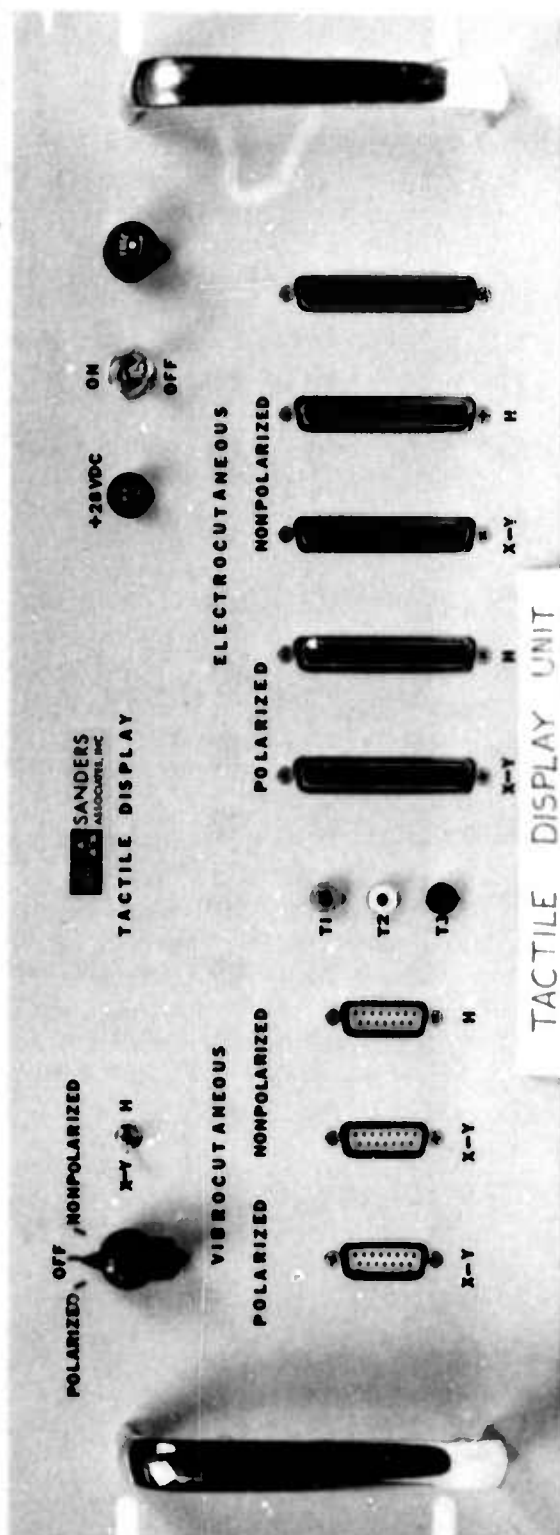


Figure 3-13 Tactile Display Unit.

SECTION 4

PRELIMINARY DISPLAY EVALUATION

This section reports the results of a series of experiments, performed at Sanders' Merrimack facility, using the various displays described in the previous chapter. The purpose of these experiments was to investigate the relative effectiveness of display configurations and modes of data presentation.

In the first set of experiments the subject was required to judge numbers of tactors activated and their location on the skin, and the rate of activation of a sequence of tactors. In the second set of experiments the subject used the tactual displays in a tracking task.

There are three basic display configurations:

1. A circle of 21 tactors
2. A polarized X-Y array of 13 tactors
3. A non-polarized H of 12 tactors

Within the three configurations a number of other spatial and coding variations are possible. These are discussed fully in the previous chapter. Since the number of possible experimental conditions is so large, we have directed our efforts towards identifying parameter values acceptable for a tracking experiment rather than attempting an exhaustive study of the effects of variations of parameters over a wide range of values.

4.1 CIRCLE DISPLAY

The circle display consists of 20 electro-cutaneous tactors arranged in a circle of 2 or 4 inch radius plus one tactor in the center. The mode of display chosen for this experiment was the sequential activation of three tactors in a line which included the center tactor. In this mode there are a total of twenty different sequences possible, one beginning on each of the 20 circumferential tactors. (Equivalently, there are 10 lines passing through the center tactor and the tactors in each line may be "strobed" in either of two directions.)

A trial consisted of a single sequence of three tactors. Subjects were required to identify the number of the first tactor in the sequence. Intertactor interval was the independent variable. The three tactors were either activated simultaneously or with 10, 50, 150 or 250 milliseconds between activation of individual tactors.

The individual tactors were excited with eight 50 microsecond pulses delivered at a 250 Hz rate. For each subject four series of runs were made, each consisting of twenty trials at each of the five intertactor intervals, for a total of eighty trials at each intertactor interval.

Each set of twenty trials contained one each of the twenty possible display sequences. Data were taken for three subjects. Errors were scored, and called gross errors when the response differed from the input signal by more than two circumferential tactors or "units". An error of three units or more or an error in perceiving the direction of strobing (a reversal error) was scored as an error of 3 units. A separate tabulation of gross errors and of reversal errors was made.

Results:

Results are presented in graphical form, Figures 4-1 through 4-4. For the five intertactor intervals chosen, the average error on a given trial was about one unit (or 18°) for two inch tactor spacing and about $3/4$ unit for four inch spacing. Taken overall, the discrimination performance was superior at the larger spacing. The average error decreased only slightly with increasing intertactor time interval. There was more confusion of the direction of sweep at shorter intertactor intervals. At 10 millisecond interval a larger intertactor spacing made the confusion greater.

The effect we are seeing here may be a result of limitations in the human information processing system. When two stimuli are presented in close temporal sequence, the processing of the first interfered with the requirement to process the second. The processing delay for the second signal is commonly referred to as the psychological refractory period and depends on the inter-stimulus interval.

If the second stimulus is presented during the refractory period, it cannot be processed normally, but if the interstimulus interval decreases to a very small value, both signals can be received and "grouped" so they can be handled together rather than sequentially. We see in this experiment a suggestion that a larger number of gross errors occurring at 50 ms intertactor interval than at 10 ms. Possibly the signals at 10 ms are received and processed "simultaneously" and it is also reasonable that we should see an increase in frequency of gross errors as intertactor interval is increased to a level when they must be processed sequentially. At the longer intertactor intervals, we would expect the interference

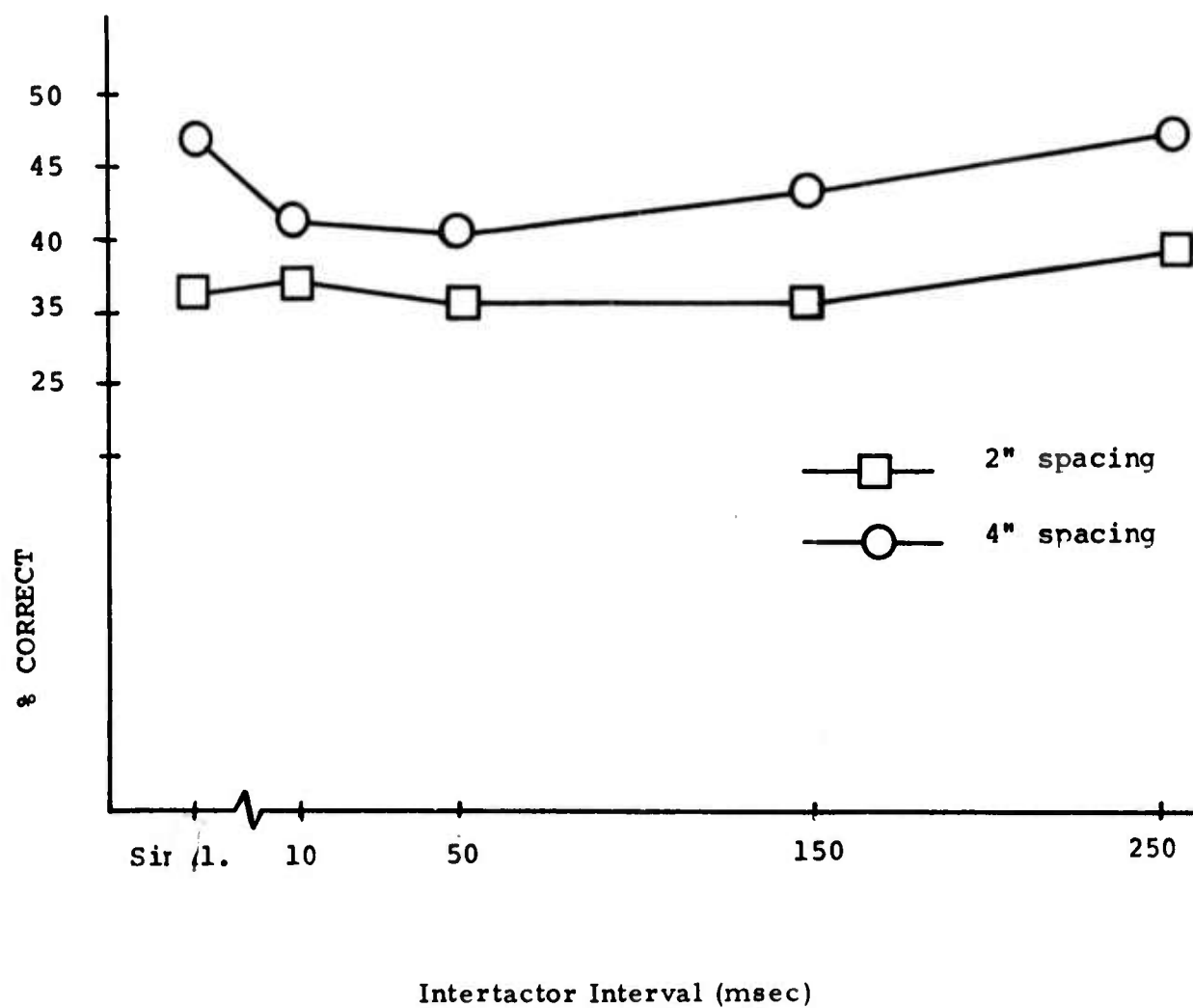


Figure 4-1 Circle Display - Comparison of Performance at Different Spacings.

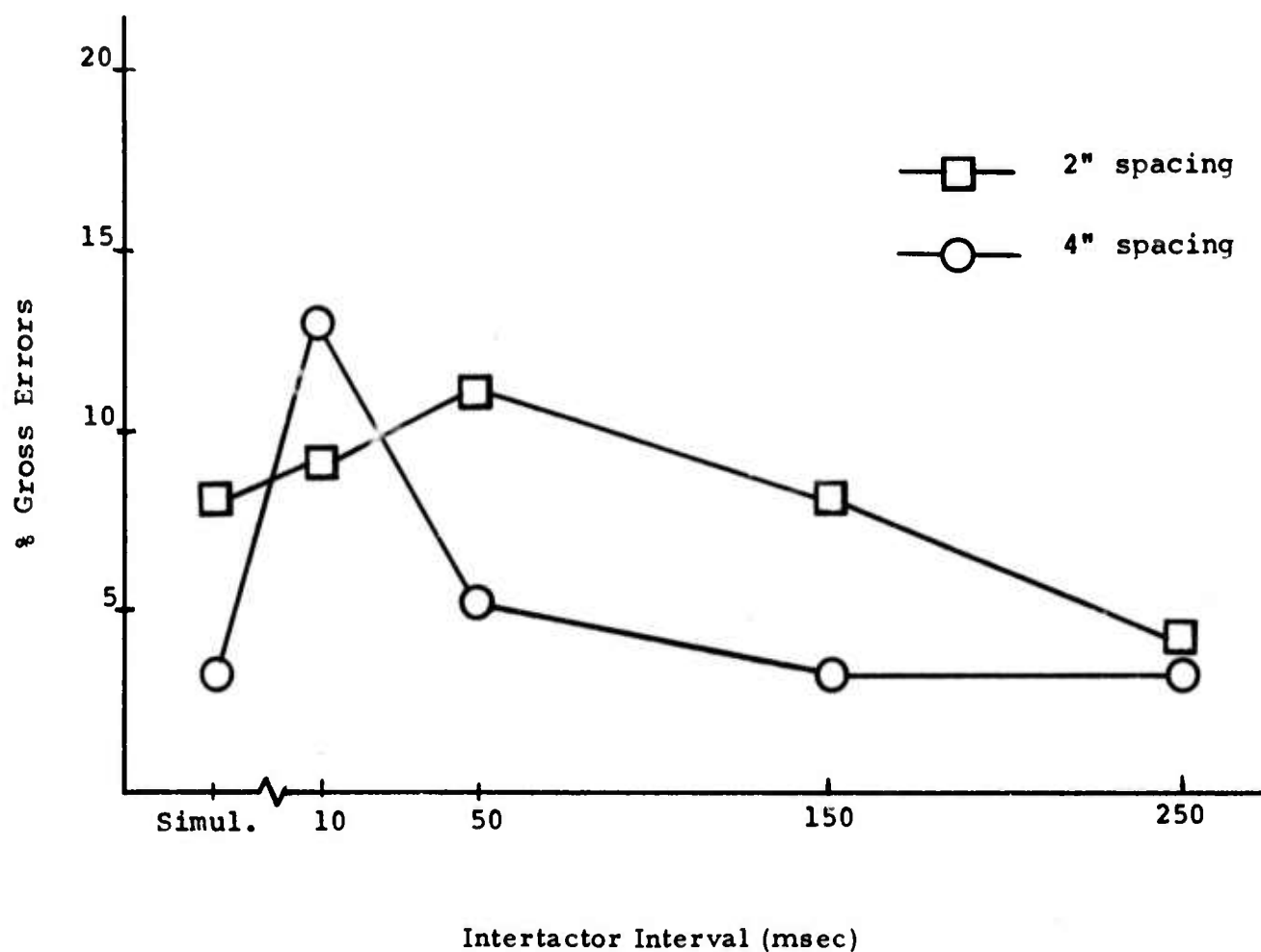


Figure 4-2 Circle Display - Comparison of Gross Error Frequency at Different Spacings.

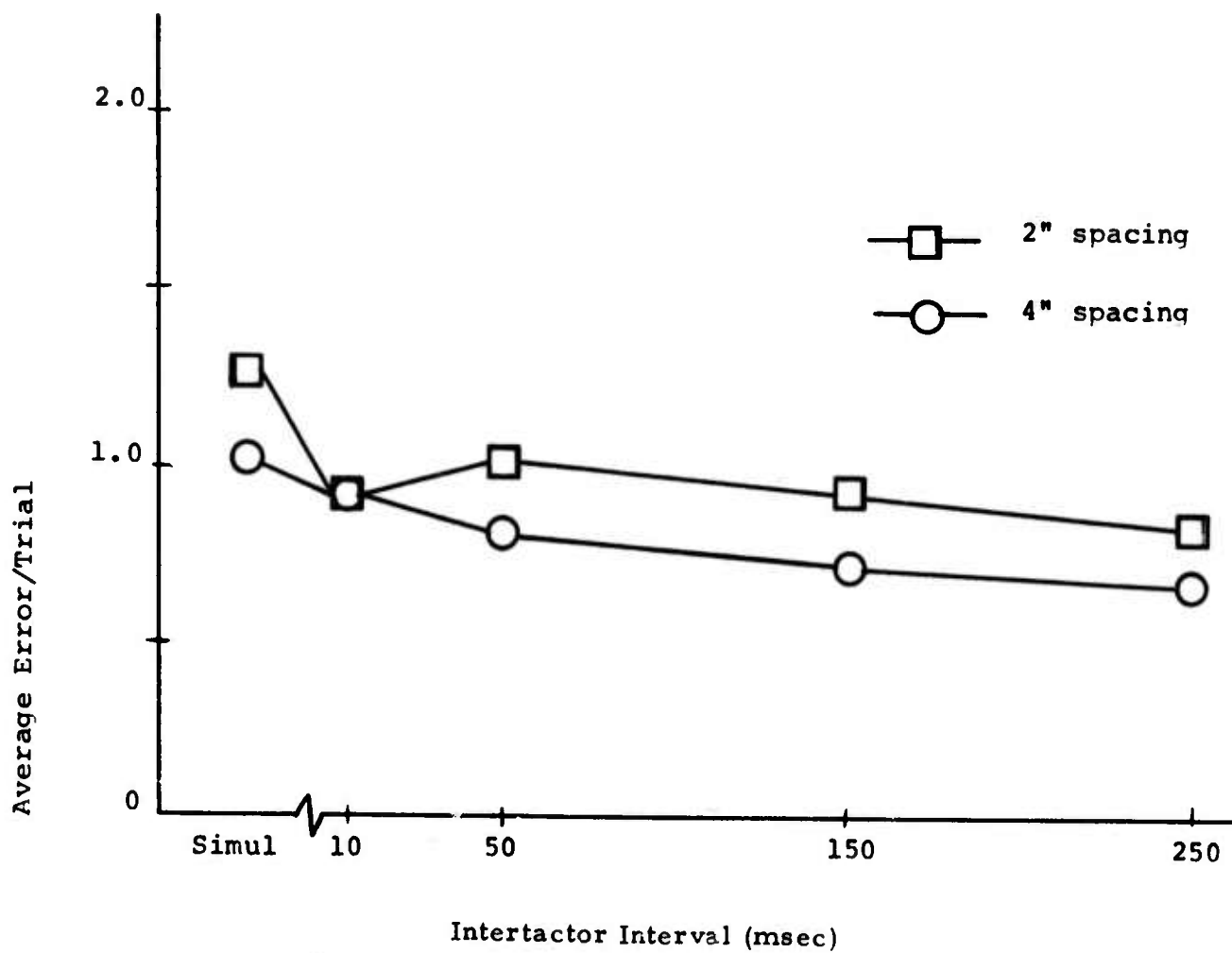


Figure 4-3 Circle Display - Comparison of Average Error at Different Spacings.

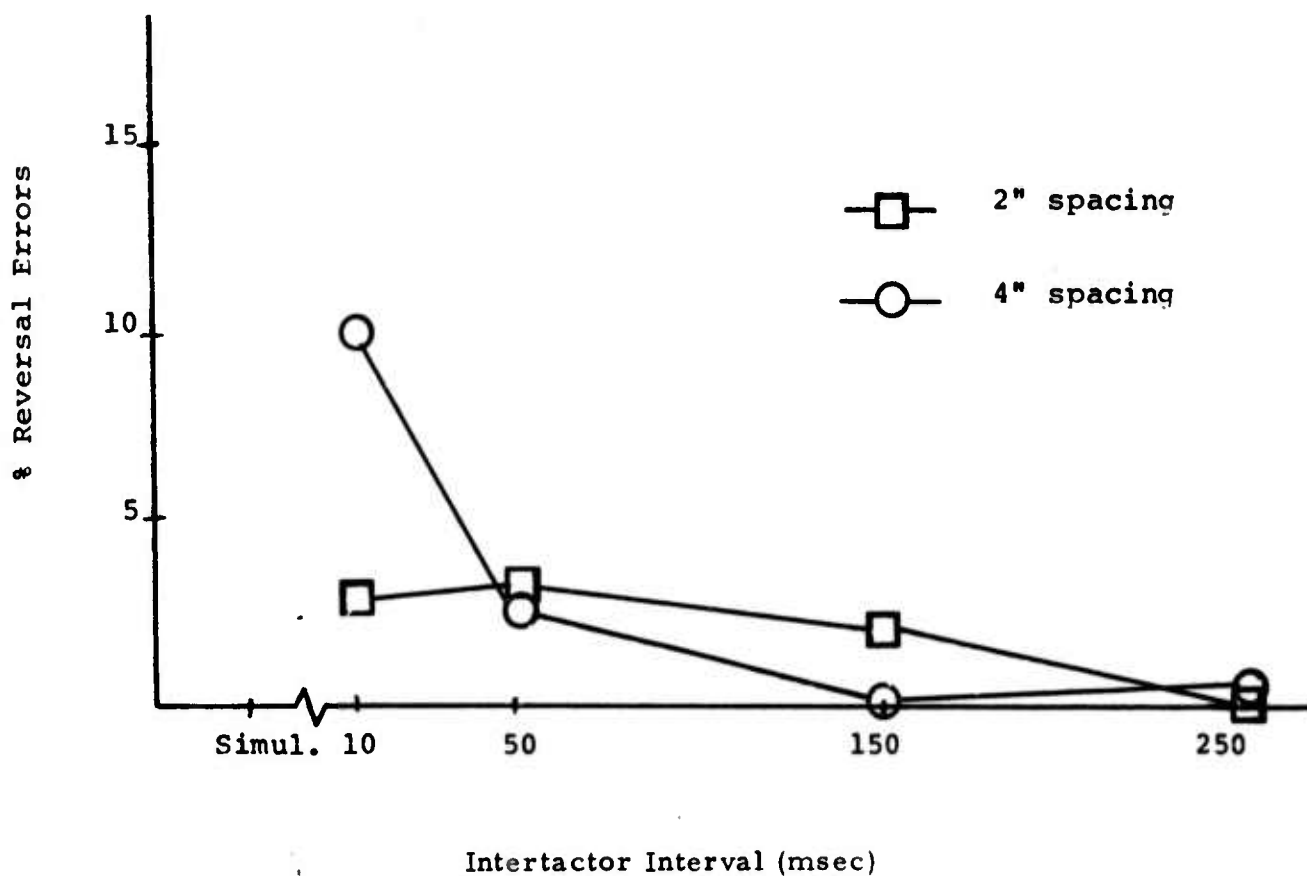


Figure 4-4 Circle Display - Reversal Errors as a Function of ITI and Spacing.

between the two signals to decrease, and a smaller error rate to result. This is in fact borne out in the data.

4.2 POLARIZED X-Y DISPLAY, NUMBER AND RATE JUDGMENTS

The array consists of 13 tactors, seven in a line crossing on a common tactor. During this series of experiments, the mode of data presentation consisted of sequential activation of tactors beginning in each case with the center tactor and sweeping outwards. The two axes were activated alternately, where a two axis display cycle consisted of a sweep of tactors in the X (horizontal) direction, then a sweep in the Y (vertical) direction. The time between the completion of the X sweep and the beginning of the Y sweep (or the beginning of another X sweep or the single axis case) could be varied and is termed interaxis "dwell".

The electrotactor display with 0.75 inch intertactor spacing was used throughout this series of experiments. When no signal was being presented the center tactor was activated periodically as a reference. The period of the reference tactor was changed after the first day of these experiments from one second to seven seconds for reasons which are explained below.

The subject was given training on each new set of experimental conditions before data were taken. Training times were typically of the order of ten minutes.

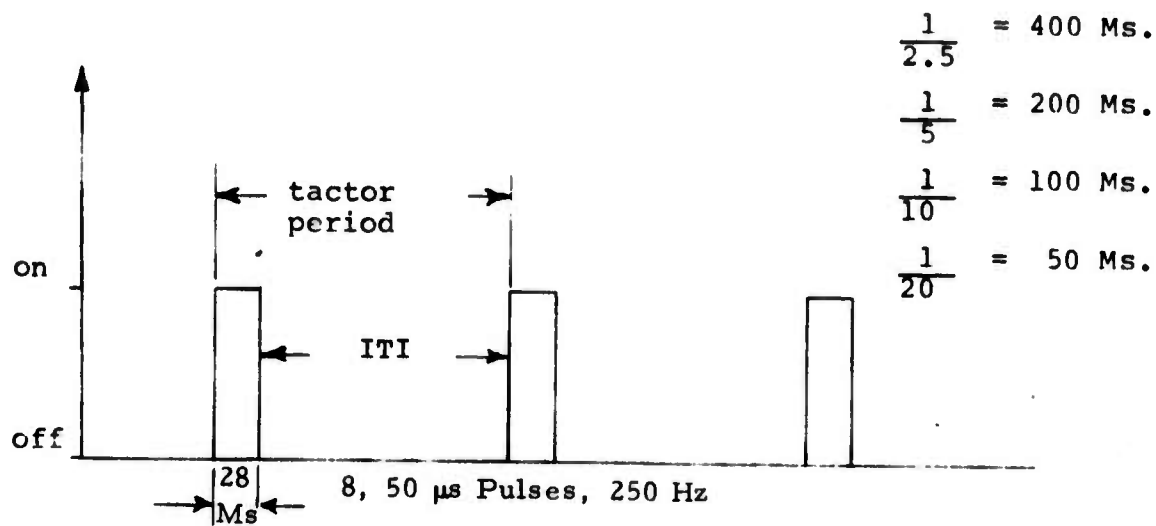
During data taking trials, the signal was repeated until the subject responded. It was considered that, with the parameter values chosen for this series of experiments making judgments based on information from a single sweep was essentially impossible, and this was borne out in pilot experimentation.

4.2.1 JUDGMENTS OF NUMBER OF TACTORS

The subject was required to identify the number of tactors activated in a display sequence. Single axis data runs of thirty five trials each were made at each of two tactor sweep ratios and two interaxis dwell lines. A trial consisted of the presentation of a sequence of from one to four tactors, sweeping outward from the center. The two tactor rates were 10 and 20 Hz and the two values of interaxis dwell time were 150 ms and 250 ms for these single axis experiments. See Table 4-1 for correspondence of tactor rate and intertactor interval.

Two-axis data runs consisted of 40 judgment trials. In four trials no signal was presented; in twelve, signal appeared only on one axis. In the remaining twenty-four trials signals appeared on both axes in sequence. Two blocks of data runs were obtained: In the first, interaxis dwell time was 150 ms for two axis trials, and 250 ms between cycles when only one of the two axes was displaying error. In the second block, dwell times were 250 ms for two axes and 375 for one axis trials. Tactor rate was 20 Hz for both runs.

TABLE 4-1
RELATION OF TACTOR RATE AND
INTERTACTOR INTERVAL



$$\dot{T} = \frac{1}{\text{Tactor Period}}$$

$$\text{ITI} = \text{Tactor Period} - 28 \text{ ms}$$

Tactor Rate or Frequency \dot{T}	Intertactor Interval ITI
2.5 Hz	372 ms
5.0 Hz	172 ms
10.0 Hz	72 ms
20.0 Hz	22 ms

Results:

Results are presented in tabular form, Tables 4-2 and 4-3. Since confusion of number of active tactors did not seem to occur more frequently for any single number, and since no error was of greater than one unit in magnitude (e.g., calling a 3 or 4), total errors in a run are simply added. Single axis runs did not produce an error rate high enough to demonstrate sensitivity to variations in parameters (or, alternatively the range of parameter values was not sufficient to influence error rate).

The tactor rate was high enough so that determining the number of active tactors was not merely a matter of counting pulses. The sensation was one of a continuous stroke across the skin for the 20 Hz tactor rate. At 10 Hz, pulses were felt, but were barely distinguishable as individual pulses in the continuous stroke.

Two sets of single axis runs were made. Analysis of the first day's data showed a tendency for the subject to underestimate the number of tactors displayed in a given trial. This fact was consistent with an observation that the center tactor became less distinguishable as time progressed because of sensory adaptation to the repeated stimulation of the reference tactor which was being pulsed once per second. On the second day, in order to reduce the frequency of stimulation as far as possible, the period between reference pulses was increased from one second to seven seconds and remained so during the subsequent tracking experiments.

For the second experimental session, it was found that the two conditions where error was displayed on only one axis did not produce the underestimation of tactor number observed in the data from the first day. However, the subject observed that the center tactor remained more distinguishable throughout, then tending to confirm the hypothesis that adaptation of the center tactor led to underestimation of the number of tactors stimulated. However, it is well to point out that the overall error was low, and as such estimation of the prevailing type of error was difficult.

Comparison of the data from the two axis runs suggests a decrease in error rate with increasing dwell time. Recalling our psychological refractory period discussion from the previous experiment and noting from Table 4-1 that the intertactor interval at the 20 Hz tactor rate is 22 ms, we suggest that a significant amount of information processing for one axis must take place during the pause between data presentations. The dwell times in the two axis runs are of the same order as the total stimulus presentation period in the circle display experiment when the interstimulus interval was set at 250 milliseconds.

In the two axis trials, there is a tendency to overestimate the number of active tactors. The one-axis trials which are interspersed with the two axis

TABLE 4-2
SINGLE AXIS JUDGMENTS OF NUMBER
OF TACTORS

Experiment	Number of Errors		
	Overestimation	Underestimation	Total
Variable: Number of Tactors N.T. = 1, 2, 3 or 4 Dwell 150 ms $\dot{T} = 10$ Hz Run 1 Run 2 Center Tactor Reference Period 1 Second	 0 1	 4 2	 4 3
Variable: Number of Tactors N.T. = 1, 2, 3 or 4 Dwell 150 ms $\dot{T} = 20$ Hz Run 1 Run 2 Center Tactor Reference Period 7 Seconds	 2 0	 1 5	 3 5
Variable: Number of Tactors N.T. = 1, 2, 3 or 4 Dwell 250 ms $\dot{T} = 20$ Hz Run 1 Center Tactor Reference Period 1 Second	 0	 2	 2

Subject made no gross errors (errors ≥ 2) and no errors involving sign reversal.

Each data group consists of 35 trials requiring 1 response each.

Polarized x-y display, 0.75 inch spacing, subject RBT.

TABLE 4-3
TWO AXIS JUDGMENTS OF NUMBER
OF TACTORS

Experiment	Number of Errors				Total
	Overestimation	Underestimation	Response When No Signal	No Response to Signal	
Variable: Number of Tactors N.T. = 1, 2, 3 or 4 Dwell: 1 Axis: 225 ms 2 Axis: 150 ms	10	9	1	4	24
Variable: Number of Tactors N.T. = 1, 2, 3 or 4 Dwell: 1 Axis: 375 ms 2 Axis: 250 ms	10	3	1	2	16

Subject made no gross errors (errors ≥ 2) and no errors involving sign reversal.

Each data group consists of 40 trials requiring 2 responses each (1 per axis), 24 trials have signal on 2 axis, 12 trials have signals on 1 axis, 4 trials are reference signals only.

Polarized x-y display, 0.75 inch spacing
Tactor rate, \dot{T} - 20 Hz
Subject RBT

show the same tendency to underestimate as noted in the one axis runs. It is interesting to note that even at this high tactor strobe rate there was no confusion of the direction of the sweep. The subjects, however, did show a low rate of reversal errors at short intertactor intervals in the previous circle display experiment.

4.2.2 RATE JUDGMENTS

Conditions were the same as for the previous experiment with the exception that the subject was required to discriminate between four tactor rates, 2.5, 5, 10 and 20 Hz. All four tactors for any given axis and direction were active during tactor rate experiments. After training, a single data group of 20 trials was recorded for the one-axis task. Two blocks of data trials at different dwell times were made for the two-axis task. For the two axis trials, a signal was presented in sequence to both axes. Each data group consisted of a tactor rate and a direction.

Results:

Results are presented in Tables 4-4 and 4-5. Again, the error rate in the single axis case is low. There is a tendency to underestimate rates in the single axis case and to overestimate in the two-axis case. The underestimation is possibly caused by the adaptation effects discussed earlier. The overestimation in the two-axis judgment trials is more difficult to understand. It possibly could result from the subject tending to let his judgments of the slower strobe rates be raised by the presence of a faster strobe rate on the other axis. Error rate appears to decrease with increasing dwell time for two axis in the same way as was found for the judgments of number of tactors in the previous experiment for the same dwell times.

The four tactor rates were easily differentiable when presented sequentially in descending order of strobe rate. The 20 Hz rate was previously described as a continuous strobe, the 10 Hz rate a strobe with individual pulses discernible. The 5 Hz rate caused clearly separate pulses; the 2.5 Hz rate was more "insistent" than 5 Hz, rather like a pencil point tapping. When different rates were presented out of sequence at random, they were more difficult to judge as the error rates in the data show. There was no rate which caused a disproportionate number of errors; there were no errors of greater than one rate increment.

4.3 TRACKING EXPERIMENTS

In this series of experiments, a number of displays were incorporated in a tracking task. The subject controlled a two-axis first order system (K/S dynamics on each axis) by means of a two axis joystick spring loaded to center. The subject was required to null step-inputs, and the time to null was recorded.

TABLE 4-4
SINGLE AXIS - RATE JUDGMENTS

Experiment	Number of Errors		
	Overestimation	Underestimation	Total
Variable: \dot{T} $\dot{T} = 2.5, 5, 10 \text{ or } 20 \text{ Hz}$ Dwell: 150 ms 4 Tactors Active on Each Trial	0	3	3

Subject made no gross errors (errors ≥ 2) and no errors involving sign reversal.

The data group consists of 20 trials requiring one response each.

Polarized x-y display, 0.75 inch spacing, subject RBT

TABLE 4-5
TWO AXIS - RATE JUDGMENTS

Experiment	Number of Errors			
	Overestimation	Underestimation	Sign Reversals	Total
Variable: Tactor Rate $\dot{T} = 2.5, 5, 10 \text{ or } 20 \text{ Hz}$ Dwell: 1 Axis: 225 ms 2 Axis: 150 ms 4 Tactors per Axis Active on Each Trial	10	2	2	14
Variable: Tactor Rate $T = 2.5, 5, 10 \text{ or } 20 \text{ Hz}$ Dwell: 1 Axis: 375 ms 2 Axis: 250 ms 4 Tactors per Axis Active on Each Trial	8	0	0	8

Subject made no gross errors (errors ≥ 2).

Each data group consists of 30 trials requiring 2 responses each. A response is magnitude + sign.

Polarized x-y display, 0.75 inch spacing, subject RBT.

Two subjects participated in the initial tracking experiments, but the difficulty of the task and the number of experimental conditions to be studied caused us to focus our efforts on training and gathering data from one subject. The subject had participated as a subject in extensive tracking experiments previously and had spent approximately 100 hours tracking K/S dynamics. We, therefore, allowed the subject to train until he felt confident that he had the particular system well practiced and then recorded experimental data. Training times were typically a half hour per condition.

Experiments will be discussed individually in the following sections. The equipment was discussed in detail in the previous chapter.

4.3.1 POLARIZED X-Y DISPLAY, 0.75 INCH SPACED ELECTROTACTORS

The thirteen tactor x-y display with 0.75 inch intertactor spacing was operated in the polarized mode, i.e., with tactors sweeping from the center out to display error. For the two axis task, tactors displayed error on each axis sequentially.

Control system error influenced both the number of tactors and the error rate. The number of active tactors decreased as the error neared zero, increasing the resolving power of the display.

Three sets of twelve single-axis trials and five sets of twelve two-axis trials were carried out.

Time-to-null data was recorded by stopwatch. Null error was determined by the experimenter viewing a two-axis visual-display of tracking error. The timing was terminated when the system was under control at zero error.

Results:

Results of this experiment (and of all tracking experiments) are presented in Figure 4-5. This was the first tracking experiment. The effect of learning is clearly seen in the two axis data. Data within each histogram figure is presented in chronological order. Standard deviations shown are based on the ensemble data.

4.3.2 POLARIZED X-Y DISPLAY, 1.25 INCH SPACED ELECTROTACTORS

Experimental conditions are the same as for the previous experiment except the intertactor spacing is 1.25 inches.

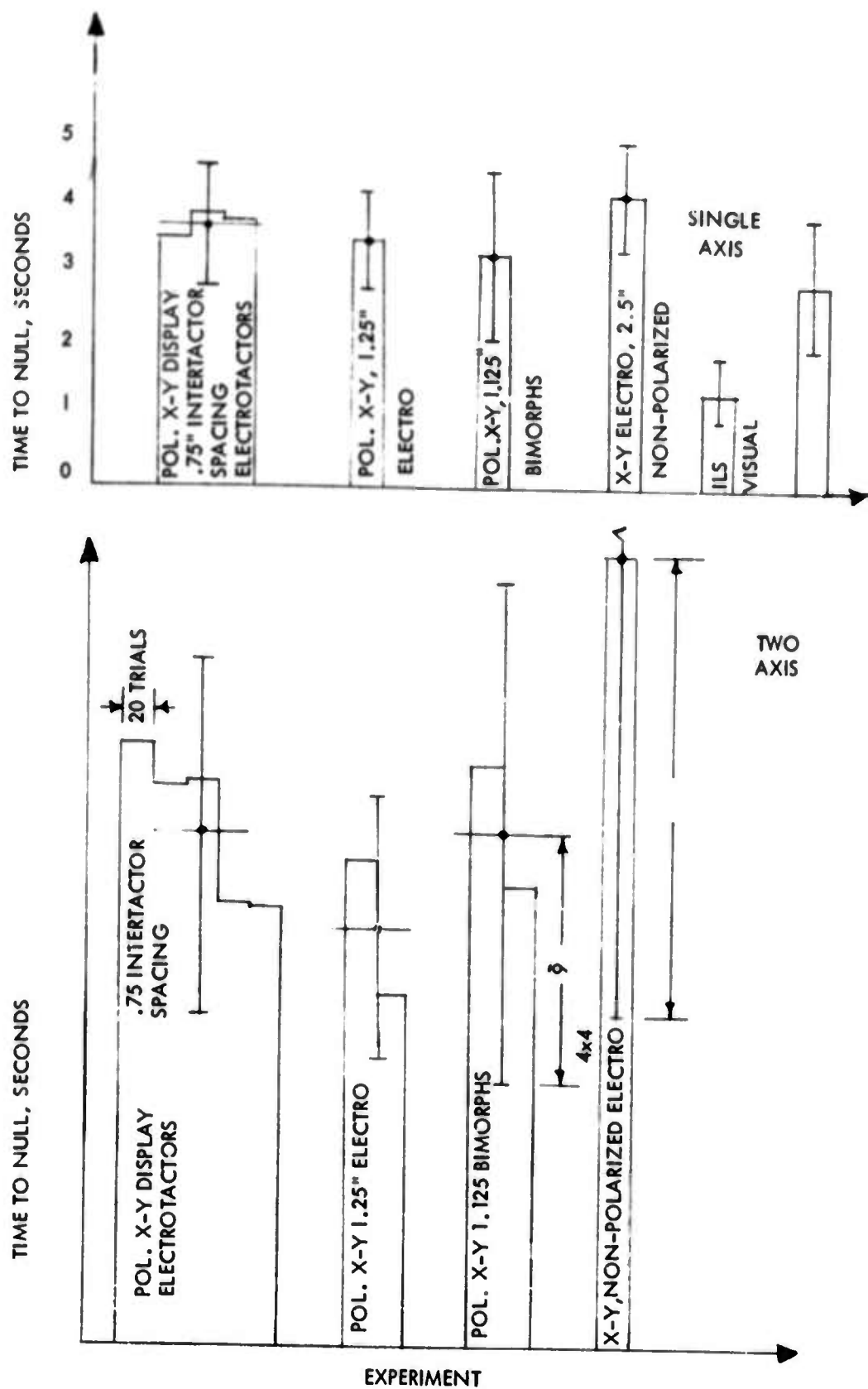


Figure 4-5 Step Input Tracking Experiments.

Results:

1.25 inch intertactor spacing appears to give shorter times-to-null than 0.75 inch spacing. There is no substantial difference in the subjective "feel" of the systems.

4.3.3 POLARIZED X-Y DISPLAY, 1.125 INCH SPACED BIMORPHS

Experimental conditions are the same as for the previous experiment.

Results:

Training time for this experiment was short since this system appeared so similar to the electrotactor systems. The large standard deviation value on time scores makes an interesting contrast with that shown with the electrocutaneous displays indicating that the subject would have profited from a greater training time. Given that the average error will decrease also when the standard deviation drops, it appears that the bimorph display should yield tracking data comparable to the electrotactor display of the same size. In terms of general comfort to the wearer, the mechanical form of stimulation is more readily acceptable than the electrocutaneous display.

4.3.4 NON-POLARIZED X-Y DISPLAY, 2.5 INCH SPACED ELECTROTACTORS

Conditions were similar to the previous experiments, except the 2.5 inch electrotactor display was operated in the non-polarized mode. In this mode, the signal begins on one side of the display and sweeps to the other, activating a total of four tactors per axis.

Results:

Times-to-null for the two axis condition are substantially longer than for the other displays. Single axis times are slightly longer. This result was in fact contrary to our initial expectations. It may be that further training time may have improved performance significantly on this display which involved a display format significantly different from the other displays tested. Furthermore, the effective spacing of tactors was greater than in the previous cases. More data are required before we can pronounce on the time merits of a non-polarized display.

4.3.5 VISUAL TRACKING EXPERIMENTS

The experimental conditions remained the same, but the tactual display was exchanged: First for an ILS analog display, then for the visual analog of the polarized X-Y display shown in Figure 3-10.

Results:

The ILS display could usually be brought to zero in a single motion by a bang-bang (or step displacement) strategy, and yielded the best time-to-null score of all the displays tested. For the visual LED display, the times-to-null were only slightly better than for the tactual display.

4.3.6 NON-POLARIZED H DISPLAY, ELECTROTACTORS

In the final experiment, the subject attempted to track using the H display utilizing 12 electrotactors. This system was very different from previous systems, and had poor display-control compatibility. Because of this compatibility problem, it was not possible with a limited training time to allow the subject to null the displayed error easily compared with only the few minutes of training required in order to null the X-Y display relatively quickly.

Based on subjective impressions, it is likely that this display, given adequate training and good display-control compatibility, can yield reasonable performance. However, these initial data cast some doubt on the worth of this display configuration.

4.4 CONCLUSIONS

It has been demonstrated to be possible to null step-inputs in a two-axis first order tracking task using tactual displays. An electrocutaneous display and a mechanical bimorph display yield similar step-tracking scores. Increasing intertactor spacing appears to improve step-tracking performance. Tracking a visual analog of one of the tactual displays yields scores only slightly superior to the tactual display. Tracking steps-inputs using a visual display which presents an analog (continuous) signal gives significantly better scores than any tactual system tried to date. However, it should be emphasized here that subjects were permitted to devote their full attention to the tracking task and were not subjected to an additional visual distracting task.

The non-polarized X-Y and H displays will require further evaluation before their effectiveness can be compared with that achieved using the X-Y display in the polarized mode.

SECTION 5

PROGRAM PLAN FOR REMAINDER OF CONTRACT

The remainder of the contract period will consist primarily of a formal experimental and analytical program which has the following three basic objectives: (1) final selection of tactual display parameters, (2) determination of the suitability of tactual displays for flight control, and (3) characterization of pilot-display interactions in quantitative terms.

After a final preliminary experiment has been performed to provide a comparison of the H and X-Y display geometries, the formal experiments on continuous manual control will commence. The first such experiment will be designed to allow a final selection of tactual display parameters, while the remaining experiments will indicate the suitability of tactual displays for flight control. Pitch-and-roll control task will be simulated, and a visual search task (not directly related to the primary control task) will be provided during some of the experimental trials. Analysis of these results in terms of an appropriate pilot/vehicle model will enable us to predict the suitability of the tactual display for flight situations beyond the pitch and roll tasks studied in this program.

BBN's "optimal-control" model for pilot/vehicle systems (described briefly in Section 7 of this report) will be used to quantify the interaction between the pilot and the display. This model contains parameters which appear to relate directly to basic information-processing limitations of the human controller. In particular, we expect that the difference between visual and tactual displays will be reflected primarily as changes in parameters related to information-transmission delay and to display-related "noise".

The program schedule for the remainder of this contract is shown in Figure 5-1. The planned experimental program and the analysis procedures are described in Sections 6 and 7, respectively.

1973						
	JAN	FEB	MAR	APR	MAY	JUN
FINAL PRELIMINARY EXPERIMENT		◆				
SETUP AND INITIAL TRAINING ON CONTINUOUS CONTROL	◆	◆				
FIRST FORMAL EXPERIMENT		◆	◆			
SECOND FORMAL EXPERIMENT		◆	◆			
THIRD FORMAL EXPERIMENT (OPTIONAL)			◆	◆		
DATA ANALYSIS		◆	◆	◆	◆	
FINAL REPORT				◆	◆	◆

Figure 5-1 Program Schedule.

SECTION 6

EXPERIMENTAL PROGRAM

6.1 SIMULATION FACILITY

BBN's simulation facility is especially well-equipped for studies of the human as a controller of dynamical systems. Both analog and digital computing machinery are available for simulating system dynamics, driving displays, and computing performance measures. Displays and controls are located in a subject booth that is isolated visually and acoustically from the environment.

6.1.1 EXPERIMENTAL CONFIGURATION

Figure 6-1 diagrams the experimental configuration that we propose to use in the tracking experiments to be performed under this contract. This system has been used successfully in the past to study the nature of pilot-display interaction (Levison, 1971 and Levison, Elkind and Ward, 1971).

The heart of the system is the Applied Dynamics AD/4 analog/hybrid system that simulates vehicle dynamics, drives the displays, and computes mean-squared errors. The Digital Equipment Company PDP-10 digital computer is used to supply the forcing function (computed pre-experiment and stored on disk file), control the analog machine, and store the data on magnetic tape. The same digital computer is used post-experiment to analyze the tracking data.

By using the digital computer to generate the forcing function, and by converting the analog tracking data into digital format at run time, we avoid the use of analog tapes and thereby eliminate one potentially important source of system noise. Minimization of system noise is important with regard to this study, because we wish to obtain accurate estimates of pilot-related "noise" associated with the various displays under investigation.

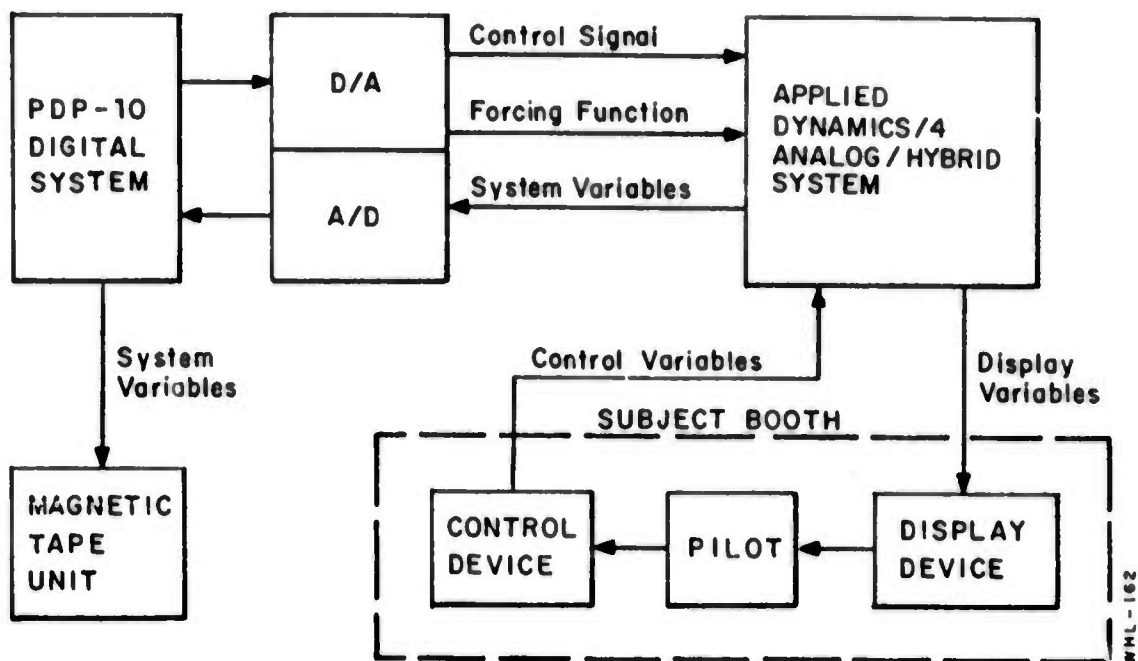


Figure 6-1 Experimental Configuration.

6.1.2 DISPLAYS AND CONTROLS

Both visual and tactual tracking displays will be used in the experimental program. The format(s) for the tactual display(s) will be selected from those described in Section 4. The visual display will consist of a CRT presentation of simulated pitch and roll. We anticipate using the idealized display format sketched in Figure 6-2.

In order to maximize transfer of learning between the tactual and visual displays, motions of the moving element of the visual display will correspond as closely as possible to motions perceived from the tactual display. Thus, a simulated pitch error which produces an upward motion of the pitch indicator will also produce an upward-directed sequence of tactual simulations. Similarly, clockwise motions of the visual roll indicator will correspond to a right-directed tactual sequence.

A two-axis hand control will provide for independent control inputs to the pitch and roll axes. As presently configured, the control is primarily a force-sensitive device and can be manipulated with wrist and finger motions. This control device has allowed for a high level of tracking precision in previous laboratory experiments using visual displays (Levison, 1971 and Levison, Elkind and Ward, 1971).

6.2 EXPERIMENTAL TASKS

The bulk of the formal experimental program will be devoted to an investigation of continuous manual tracking performance with tactual and visual displays. In addition, combined tracking and visual search tasks will be studied in order to provide comparisons between tactual and visual displays in a setting that is more relevant to flight management. The tracking and visual search tasks are described separately below.

6.2.1 TRACKING TASKS

Two very important constraints have been placed on our selection of a tracking task for the initial experiment. First, a high degree of face validity is desired. That is, the laboratory task should simulate the important aspects of a flight-control task to which a tactual display might ultimately be applied. Secondly, because of the pioneering nature of this effort, it is important to obtain an accurate and relatively complete characterization of the interaction between the pilot and the tactual display. Interpretation of the measurements obtained during simulation is greatly facilitated if each perceptual dimension of the tactual display relates to an independent single-variable control task. In this type of control situation the pilot's response to a given tactual display variable is unlikely to be confounded with his response to other tactual (or visual) display variables.

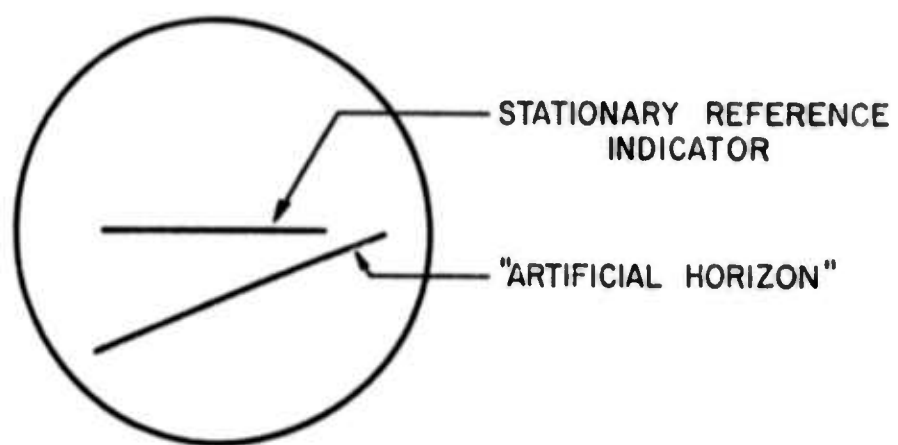


Figure 6-2 Idealized Display Format.

These two restrictions lead to the adoption of a simulated pitch/roll task, at least for the first two experiments. We tentatively plan to simulate a set of simplified pitch and roll dynamics representative of fighter aircraft having good handling qualities. The following dynamics are suggested by Neal and Smith (1970), and Boothe and Parrag (1972). For pitch dynamics,

$$\frac{\theta}{\delta_e}(s) = \frac{K_\theta (s + 1/T_\theta)}{s(s^2 + 2\zeta SW_s + W_s^2)}$$

and for roll dynamics,

$$\frac{\phi}{\delta_a}(s) = \frac{K_\phi}{s(s + 1/T_r)}$$

K_θ and K_ϕ are control gains to be adjusted early during subject training to provide desired system responsiveness. Typical values for dynamical parameters are

$$T_\theta \approx 1.0 \text{ sec}$$

$$W_s \approx 6.0 \text{ rad/sec}$$

$$\zeta \approx 0.85$$

$$T_r \approx 0.3 \text{ sec}$$

Disturbance inputs will be constructed by summing together a number of sinusoids to simulate a first-order Gaussian noise process.* This disturbance is to be applied in parallel with the pilot's control input to simulate a gust disturbance to the vehicle. We expect the "critical frequency" of the simulated noise process will most likely be 2 rad/sec. Test inputs of this type have been found in previous laboratory experiments to provide signal bandwidths that are reasonable from the pilot's point of view and generally adequate in terms of describing

* Sums of sinusoids (as opposed to filtered white noise) are used to enhance our measurement capability. With this type of input, the input-correlated component of the pilot's response is concentrated at a relatively few frequencies, whereas the random component (the "pilot remnant") is a relatively smooth function of frequency. We are thus able to achieve good signal/noise levels at measurement frequencies and thereby maximize the bandwidth over which our estimates of pilot response behavior are valid.

the pilot's response behavior. The disturbance inputs applied to the pitch and roll axes, while having similar statical properties, will be linearly uncorrelated.

6.2.2 VISUAL SEARCH TASK

In normal flight management, a pilot is required to time-share his vision among his array of instruments, and between his instrument panel and the outside world. This requirement for visual transitioning means that individual displays cannot be continuously viewed, and because of this, any individual displayed parameter will not be as closely controlled as if the pilot could continuously fixate the display of interest. It is known that there is a time and workload penalty that the pilot must pay as a result of visual scanning. Tactual flight control displays would have the advantage that the overall visual scanning requirement could be lessened, and for example would allow visual attention to be maintained continuously outside of the cockpit.

We intend to set up a visual monitoring task which will provide a significant visual scanning load for the human subject. The subject will be required to perform on both the visual or tactual tracking task and the monitoring task. Two meters will be positioned at significant horizontal offset angles (say 45° off-center), and will also be displaced vertically from the position of the CRT tracking display. Continuous displacement input will be fed to both meters independently, but the subject will only be required to respond when the pointer displacement exceeds a critical value ("a signal"). When such a displacement is observed, the subject will depress a footswitch corresponding to the meter as quickly as possible. The number of displacement signals observed will be recorded, along with the response latencies.

A monitoring task such as this cannot be performed using peripheral vision alone, and will require refixation in order to perform the task. The signals will be presented to the meters randomly over time, at a rate to be determined in pilot experimentation.

6.3 TENTATIVE EXPERIMENTAL PLAN

The proposed experimental program consists of "preliminary" experiment, training on the continuous tracking tasks, and two or three formal experiments. The tentative experimental plan is summarized below.

6.3.1 FINAL PRELIMINARY EXPERIMENT

An experiment of the type described in Section 4 will be conducted to determine performance capability with the H display. A step-tracking task will be used, with time-to-null serving as the performance indicator. Initially, performance on a single roll task will be compared with single-axis performance with the X-Y display. If performance on the H display compares favorably, a two-axis

step-tracking task will be performed using this display. Final selection of display geometry will be made on the basis of this experiment.

6.3.2 INITIAL TRAINING

Two subjects, who will be instrument-rated aircraft pilots, will be trained to a reasonable level of skill on the simulated pitch and roll tasks described in Section 6.2.1. Initial training will involve the visual display only so that the subjects may become familiar with the system dynamics as quickly as possible. On the basis of previous laboratory studies, we expect about six hours of training to be sufficient for the subjects to achieve a near-asymptotic level of performance.

The subjects will then be trained with the tactual display. Vibrotactors (bimorphs) will be used for the initial training session to maximize pilot acceptance of the tactual display. We are hopeful that a similar training period of about six hours will suffice for this display also. However, additional training will be given if, at the end of this period, trial-to-trial performance is still improving at an appreciable rate.

6.3.3 EXPERIMENT 1: FINAL SELECTION OF DISPLAY PARAMETERS

The objectives of the first formal experiment are to allow a final selection of tactual display parameters and to quantify the interaction between the pilot and the tactual display. The first data session of this experiment will indicate differences, if any, between the polarized and non-polarized display format. In addition, two sets of intertactor spacings will be explored for the non-polarized display.

The subjects will then be trained with the electrotactor displays, using the display format that proves best in the preceding test. Performance between electro- and vibro-tactile display will then be compared.

A complete set of performance measures will be obtained from the tracking results so that the effectiveness of each display configuration can be described in terms of both overall pilot/vehicle performance and pilot-related model parameters. A similar set of measures will be obtained for visual tracking in order to determine a "baseline" level of pilot proficiency that can be compared to previous experimental results.

The tactual display configuration which yields best overall performance will be explored further in the remainder of the experimental program.

6.3.4 EXPERIMENT 2: TRACKING WITH VISUAL SEARCH TASK

Visual and tactual tracking will be compared with and without an additional visual search task in the second experiment. The objective of the secondary task is to provide the type of high-workload and visually-distracting environment for which tactual displays might reasonably be considered.

Four subjects will participate in this experiment, with the two newcomers to the program receiving training on the tracking-only task explored in the previous experiment. In addition, all four subjects will receive training on the search task alone and on the combined tracking and search task.

One of the basic objectives of this experiment is to determine the suitability of well-designed tactual displays for aircraft control. To some extent, the determination will be based on the results of the combined tracking and search task, where attention-sharing requirements are expected to seriously degrade performance with the visual tracking display. In addition, the results of both formal experiments will be used in conjunction with model analysis to predict the suitability of the tactual display in situations not explored in this study. For example, the pilot-related model parameters obtained in the tracking-only experiment will allow us to predict pilot/vehicle performance when the tactual display is used to display low-bandwidth information such as flight-path information. (Indeed, we would not be surprised to find that the tactual display performs to greater advantage in the latter situation than in the pitch/roll task that we propose to study.)

6.3.5 ADDITIONAL EXPERIMENTATION

Additional experiments will be performed as time and resources permit to explore issues raised by the preceding experiments. For example, if the tactual display yields adequate pitch and roll performance, we may add a third axis of information (such as turn rate) to the display. On the other hand, if the tactual display is determined to be suitable only for low-bandwidth information, a task involving flight-path regulation might be explored. In this case, attitude information would be provided by a visual display, and flight path errors would be provided alternately by tactual and visual displays.

SECTION 7

ANALYSIS PROCEDURES

The data obtained from the formal tracking experiments will be analyzed in two ways. Primary data reduction will be performed to obtain a set of performance measures that have been commonly used in the past to describe overall system performance and pilot response behavior. Model analysis will then be performed in order to translate these results into measures that relate to basic human information-processing capability. Primary data reduction and model analysis are outlined separately below.

7.1 PRIMARY DATA ANALYSIS

Both amplitude-domain and frequency-domain measures will be obtained as follows.

7.1.1 VARIANCE SCORES

Variance scores will be obtained for both tracking error and control activity.* Error variance will serve as the primary measure of overall system effectiveness. Both control and error scores will be used in the model analysis.

7.1.2 AMPLITUDE DISTRIBUTION DENSITIES

In order to determine the effects of possible non-linearities in the pilot's response strategy, amplitude distribution densities of the control input will be obtained for selected experimental trials. If the pilot's response strategy is basically linear, his control activity should be very nearly Gaussian under the

* The "variance" of a signal is defined as the average squared difference between the instantaneous signal level and its mean. For zero-mean signals, the variance is identical to the mean-squared signal level.

experimental conditions we have described. This is true even in the presence of pilot randomness, or "noise" (where the "noise" is assumed to be essentially Gaussian).

Previous studies of pilot response behavior have shown the pilot's response activity to be nearly Gaussian under favorable display conditions (Levison, 1971). However, the same studies have shown non-Gaussian behavior under certain unfavorable display situations (such as peripheral viewing and low display gain). Hence, the interest in exploring this factor in the current study.

7.1.3 POWER SPECTRA

Power spectra will be obtained using Fourier analysis techniques based on the Cooley-Tukey method of computing transforms (Cooley and Tukey, 1965). In order to enhance the interpretability of the results, the fundamental frequency component of the Fourier analysis will be the same as the base frequency about which the forcing function is constructed. Each spectrum, therefore, consists of a set of lines, equally spaced in frequency, ranging from the fundamental frequency to a frequency that is (typically) well beyond the tracking bandwidth.

It is convenient for analytical purposes to consider each power spectrum as the sum of two component spectra: (a) the "input-correlated" spectrum, consisting only of those measurements coincident with the forcing-function frequencies, and (b) the "remnant" spectrum, consisting of the remainder of the total power spectrum. This interpretation of the measurements is based on the assumption that the remnant is a broadband continuous function of frequency having a relatively low power density level, as compared to the input-correlated portion of the signal which contains a relatively high power density level at a few selected frequencies. Thus, measurements at input frequencies are assumed to represent only the linear response of the pilot, uncorrupted by the small amount of remnant in the measurement "window". (This assumption will be tested for each spectral measurement computed from the tracking data.)

Estimates of the remnant component of the spectrum at input frequencies are needed for the computation of observation noise (discussed below) and also to provide an estimate of the signal-to-noise ratio at these frequencies. This measurement cannot be obtained directly, since there is no way to subdivide a single measurement into input-related and remnant-related components. Instead, estimates are provided by averages of the power spectral measurements obtained on either side of (but not including) an input frequency.

Average pilot describing functions will be computed to provide a convenient graphic illustration of the pilot's response strategy. If the tactical display causes an increase in effective time delay and pilot noise, as anticipated, the describing functions obtained from tactical tracking should show greater high-frequency phase

lags and lower low-frequency gain compared to the describing functions obtained from visual tracking.

Describing-functions will be obtained using the Fourier analysis techniques described above. Samples of the controller describing function - at input frequencies only - are obtained by dividing the transform of the control signal by the transform of the error signal. Estimates of the signal-to-noise ratio at each input frequency are obtained from a comparison of the power remnant power. In order to prevent the expected error in the amplitude-ratio estimate from exceeding 2 dB, estimates of the controller's describing function will be disregarded at frequencies for which either the error or control power measurement fails to exceed the corresponding estimate of remnant power by 4 dB.

7.1.4 OBSERVATION NOISE SPECTRA

The "observation noise" spectrum is obtained by reflecting the remnant-related portion of the pilot's control activity to an equivalent sensory noise process. Treating the pilot's remnant in this manner has certain advantages. One can easily compare the relative amounts of noise associated with perception of information from the various displays. In addition, one can determine from inspection whether or not the relative use of displacement and velocity information varies from display-to-display. For simple vehicle dynamics of the type intended for this study, the observation noise spectrum will appear essentially as a first-order noise process, with the critical frequency increasing as the pilot increasingly relies on error displacement information (Levison, 1971 and Levison, Baron and Kleinman, 1969).

For the experimental configuration that we plan to use, the observation noise spectrum can be computed as

$$\Phi_{rr} = |V|^2 \frac{\Phi_{uu_r}}{\Phi_{uu_i}} \cdot \Phi_{ii} \quad (7-1)$$

where $|V|^2$ is the magnitude-squared of the vehicle transfer function, Φ_{uu_r} is the remnant-related portion of the pilot's control signal, Φ_{uu_i} is the input-related portion of the control signal, and Φ_{ii} is the power spectrum of the input (Levison, 1971).

7.2 MODEL ANALYSIS

7.2.1 PRINCIPAL FEATURES OF THE MODEL

The model for human performance that we intend to apply to this study is based on the assumption that the well-motivated, well-trained human operator

behaves in a near optimal manner subject to his inherent constraints and limitations. This "optimal-control" model for the pilot has been described in considerable detail in the literature (Kleinman, Baron and Levison, 1970 and 1971). The important features of this model are summarized below for the convenience of the reader.

The pilot model contains the following principal elements:

(a) a linearized description of the vehicle dynamics given by the following state equation

$$\dot{\underline{x}}(t) = \underline{A} \underline{x}(t) + \underline{B} \underline{u}(t) + \underline{E} \underline{w}(t)$$

where $\underline{x}(t)$ is the vector which describes the state of the vehicle, $\underline{u}(t)$ is the pilot's control output, and $\underline{w}(t)$ is a vector of white driving noise processes*

(b) a "display vector" which, in general, consists of a linear transformation of the state variables and is given as

$$\underline{y}(t) = \underline{C} \underline{x}(t)$$

(c) a representation of the pilot's limitations by means of an equivalent perceptual time delay τ and an equivalent observation noise vector $\underline{v}(t)$

(d) a least-mean-squared predictor to compensate partially for the inherent time delay

(e) a Kalman filter to obtain the best estimate of the state vector $\underline{x}(t)$

(f) a set of optimal gains acting on the best estimate of the state vector.

The controller is assumed to choose his output $\underline{u}(t)$ to minimize a weighted sum of averaged display and control variances. Good approximations to the measurements obtained in a variety of single-axis tracking experiments have been obtained with a "cost functional" consisting simply of a weighted sum of system error variance plus control-rate variance. The cost on control rate represents, in part, a subjective penalty imposed by the controller on making rapid control motions. In addition, this term may account indirectly for physiological limitations on the pilot's bandwidth. The inclusion of such a term results in a "motor lag" τ_n - often associated with the neuromuscular system - which is generated in

* If the external forcing-functions are rational noise spectra of first order or higher, the resulting "input states" are incorporated in the state vector $\underline{x}(t)$.

the optimal controller. Typical values of τ_n for simple control systems have ranged from about 0.08 to 0.1 second.

Since we expect the differences between tactual and visual displays to be revealed partly as differences in effective sensory noise, we discuss the observation noise element of the model in some detail. This noise process is treated as a 'white noise' processes added to the displayed inputs. That is, each display variable utilized by the pilot is assumed to be perturbed by a noise disturbance (internal to the pilot) that is wide-band with respect to the displayed quantity. The number of such noise processes needed to characterize the pilot-display interaction is generally larger than the number of physical display indicators, since the pilot typically obtains both position and rate information from each indicator.* Thus, for a single-variable tracking situation,

$$\begin{aligned} y_p(t) &= y(t) + v_y(t) \\ \dot{y}_p(t) &= \dot{y}(t) + \dot{v}_y(t) \end{aligned} \tag{7-2}$$

where $y(t)$ and $\dot{y}(t)$ indicate displacement and rate, respectively, of the displayed error; the subscript "p" indicates "perceived" quantities; and $v_y(t)$ and $\dot{v}_y(t)$ are independent white noise signals added to error displacement and rate.

If the display gains are such that the rms values of indicator displacement and rate are well above effective threshold levels, the variance (or power density level) of each white noise process is very nearly proportional to the corresponding perceptual quantity (Levison, 1971 and Levison, Baron and Kleinman, 1969). In this case, the characteristics of the observation noise are given as

$$\begin{aligned} V_y &= P \cdot \sigma_y^2 \\ V_{\dot{y}} &= P \cdot \sigma_{\dot{y}}^2 \end{aligned} \tag{7-3}$$

where V_y and $V_{\dot{y}}$ are the variances of the noise processes $v_y(t)$ and $\dot{v}_y(t)$, σ_y^2 and $\sigma_{\dot{y}}^2$ are the variances of error indicator displacement and rate, and P is a scale factor which we shall call the "noise/signal ratio".

* There is evidence to show that displacement and velocity are perceived independently and that velocity is not obtained by differentiation of the perceived displacement (Levison, Elkind and Ward, 1971).

For the ideal display situation we have postulated, the noise/signal ratio P has been found to be largely independent of vehicle dynamics and input disturbance characteristics, and similar numerical values have been found for position and rate perception. Consequently, we consider this parameter to reflect central, rather than sensory, limitations in human information-processing capability.

For non-ideal display situations (such as low display gain or peripheral viewing), the variance of the observation noise process still appears to vary linearly with signal variance, but a non-zero "residual" noise level is obtained if the results are extrapolated to zero signal variance (Levison, 1971). In this case, the model of equation (7-3) may be extended as follows

$$V_y = P \cdot (\sigma_y^2 + \sigma_{y_o}^2) \quad (7-4)$$

$$V_{\dot{y}} = P \cdot (\sigma_{\dot{y}}^2 + \sigma_{\dot{y}_o}^2)$$

where $\sigma_{y_o}^2$ and $\sigma_{\dot{y}_o}^2$ are the "residual noise variances" which are intended to represent the effects of the pilot-display interface on pilot remnant.

7.2.2 MODEL-MATCHING TECHNIQUES

One of the important objectives of the formal experimental program is to describe the pilot-display interaction in terms of pilot-related model parameters. Accordingly, model parameters will be selected to provide a good match between model "predictions" and experimental measurements. Both amplitude-domain as well as frequency-domain measures will be used in the matching procedure.

The model-matching procedure to be used in this study will be similar to that used successfully in a previous study of display-related sources of pilot remnant (Levison, 1971). Past experience has revealed a fair degree of orthogonality among the various model parameters. For example, we have found that the values of noise-related parameters which provide the best match to the measured remnant spectrum are relatively independent of the choice of time-delay and "motor-lag" parameters (Kleinman, Baron and Levison, 1971). This circumstance simplifies the matching procedure and allows us to differentiate among the various ways in which the pilot's performance capability can be affected.

In addition to differentiating, say, between an increase in observation noise levels and an increase in effective time delay, the model-matching procedure will allow us to determine the relative degradation of position and rate perception. This analysis is possible because the break frequency of the predicted "observation noise spectrum" (see Section 7.1.5) is highly dependent on the relative

numerical values selected for V_y and $V_{\dot{y}}$. Thus, by obtaining a good match to the measured remnant spectrum, we can discover the type of perceptual degradation that has occurred relative to ideal display conditions.

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